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**Schneider et al.**

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(54) **APPARATUS AND METHOD FOR DOWNHOLE STEAM GENERATION AND ENHANCED OIL RECOVERY**


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**Related U.S. Application Data**

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(60) Provisional application No. 61/560,468, filed on Nov. 16, 2011.

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***E21B 43/243*** (2006.01)
***E21B 36/02*** (2006.01)

(52) **U.S. Cl.**
CPC ............... ***E21B 43/243*** (2013.01); ***E21B 36/02*** (2013.01)

(58) **Field of Classification Search**
CPC ....... E21B 43/243; E21B 36/02; E21B 43/16; E21B 43/162; E21B 43/24
USPC ............................ 166/256, 257, 261, 302, 59
See application file for complete search history.


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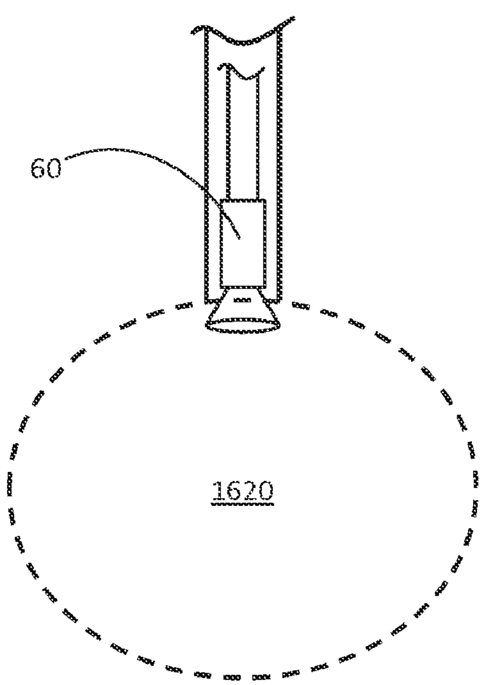
(57) **ABSTRACT**


A burner is arranged for access to a cavity in a target zone of a hydrocarbon reservoir. The burner is operated into the cavity to create and sustain hot combustion gases at a steady state for flowing into and permeating through the target zone. Water is injected into the target zone and permeates laterally therein. The hot combustion gases and the water in the target zone interact to form a steam drive front in the hydrocarbon reservoir.


**18 Claims, 18 Drawing Sheets**



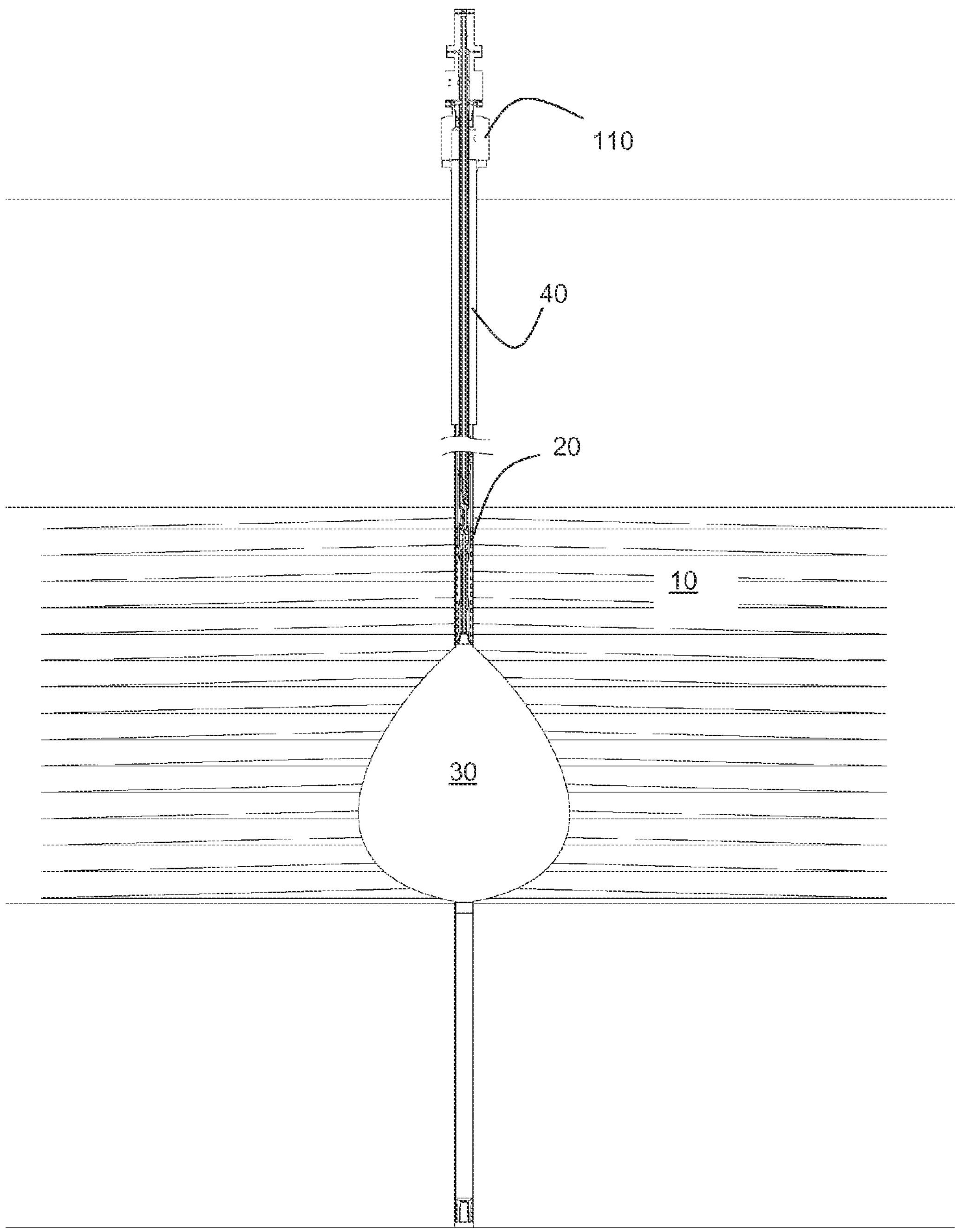



Fig. 1

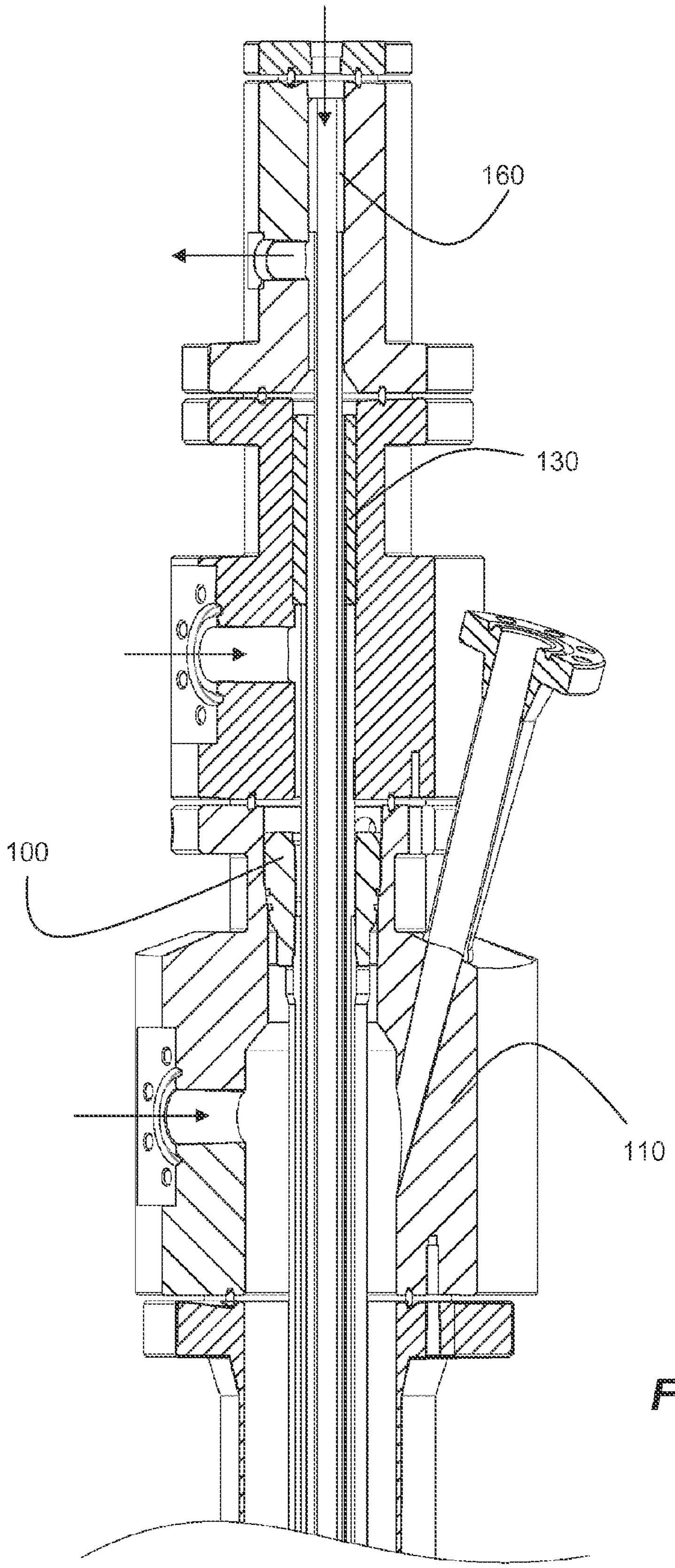



Fig. 2A

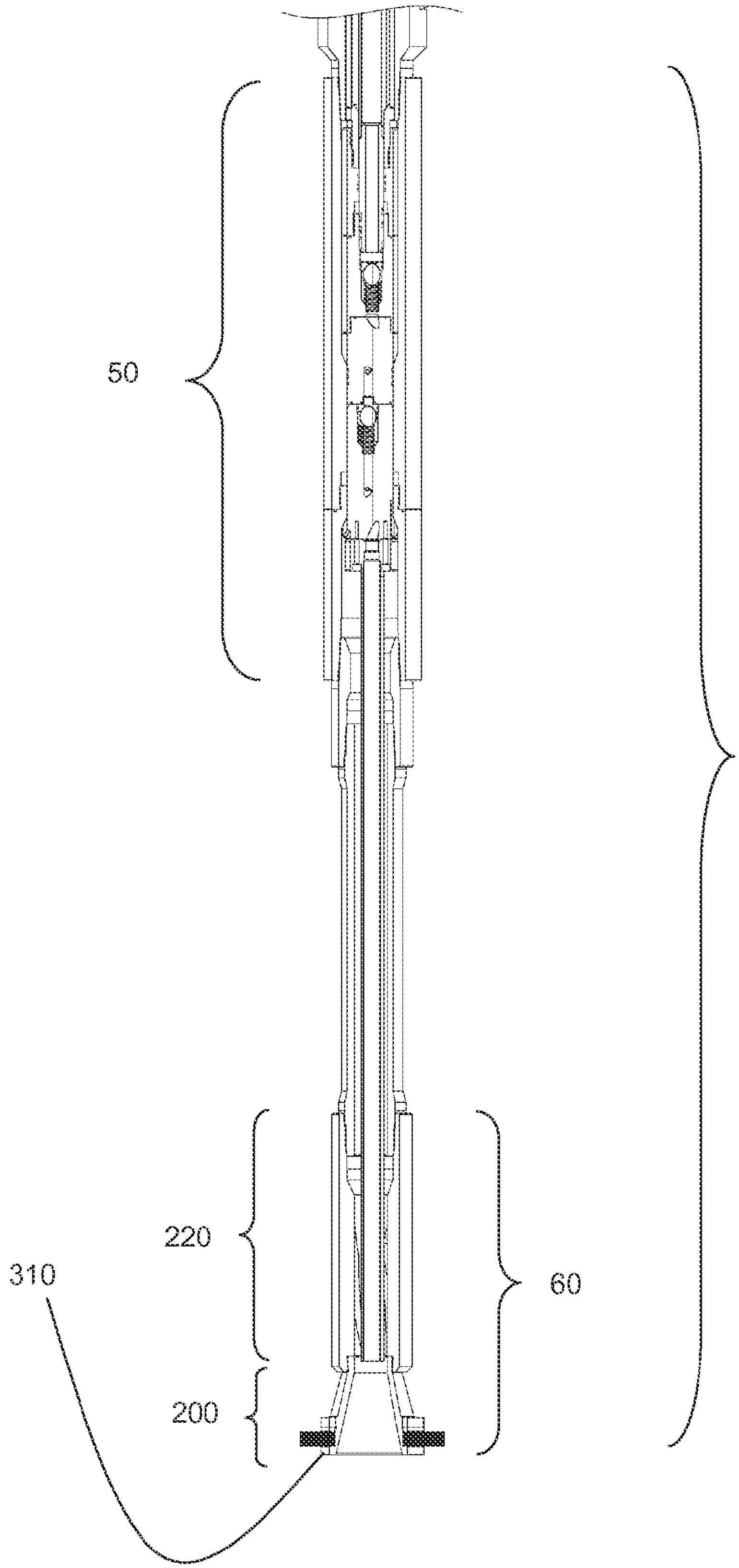



Fig. 2B

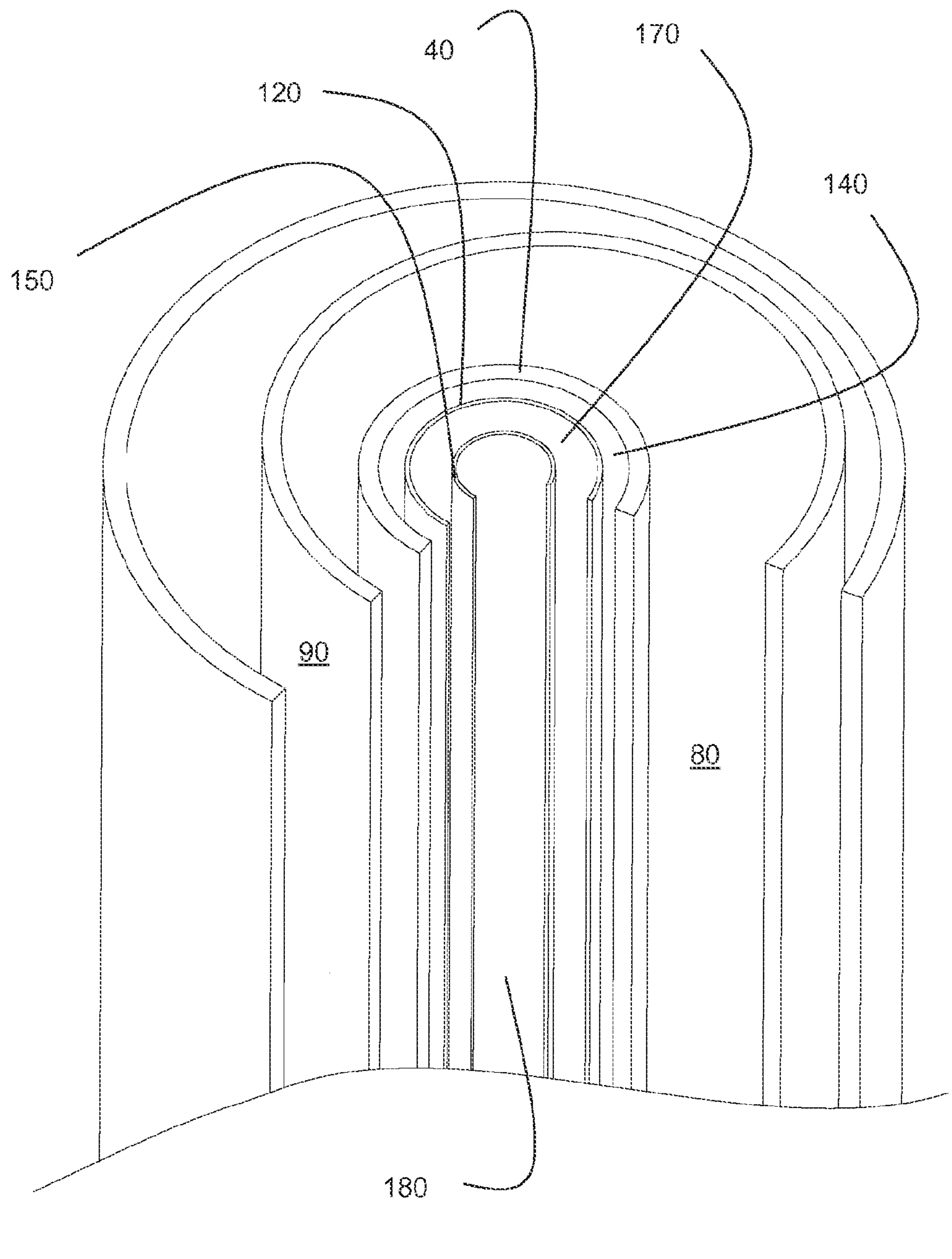



Fig. 3

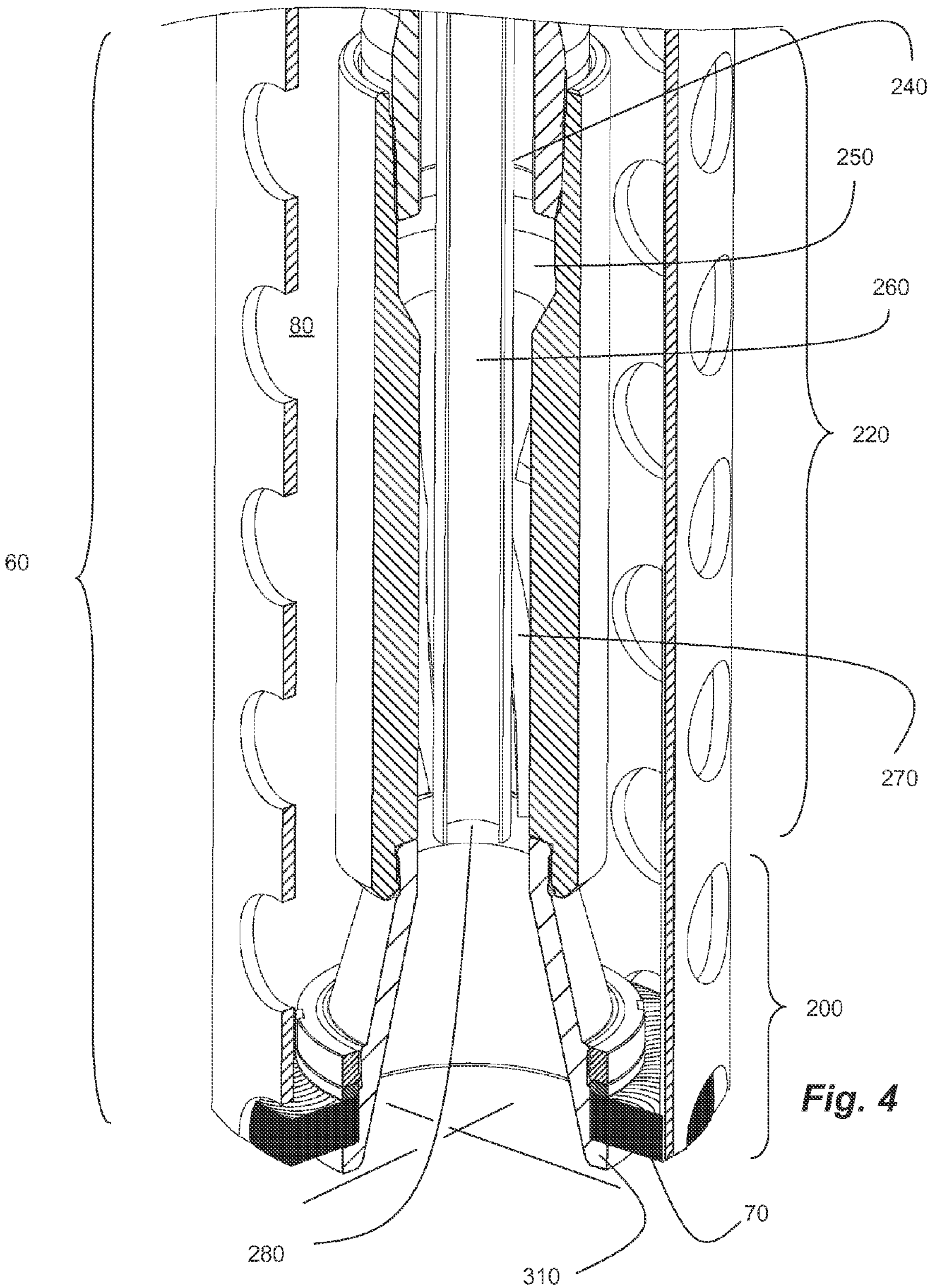



Fig. 4

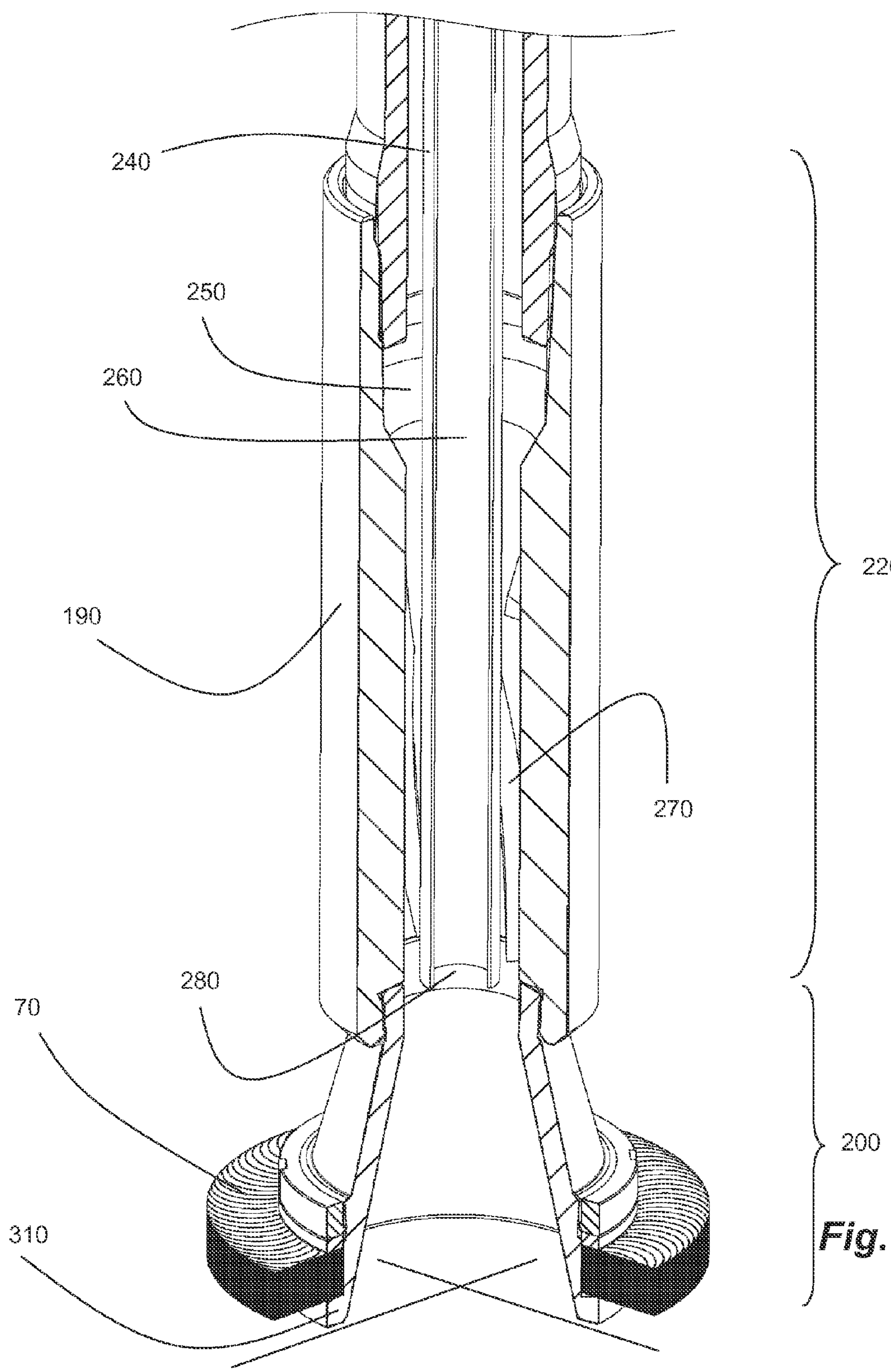



Fig. 5

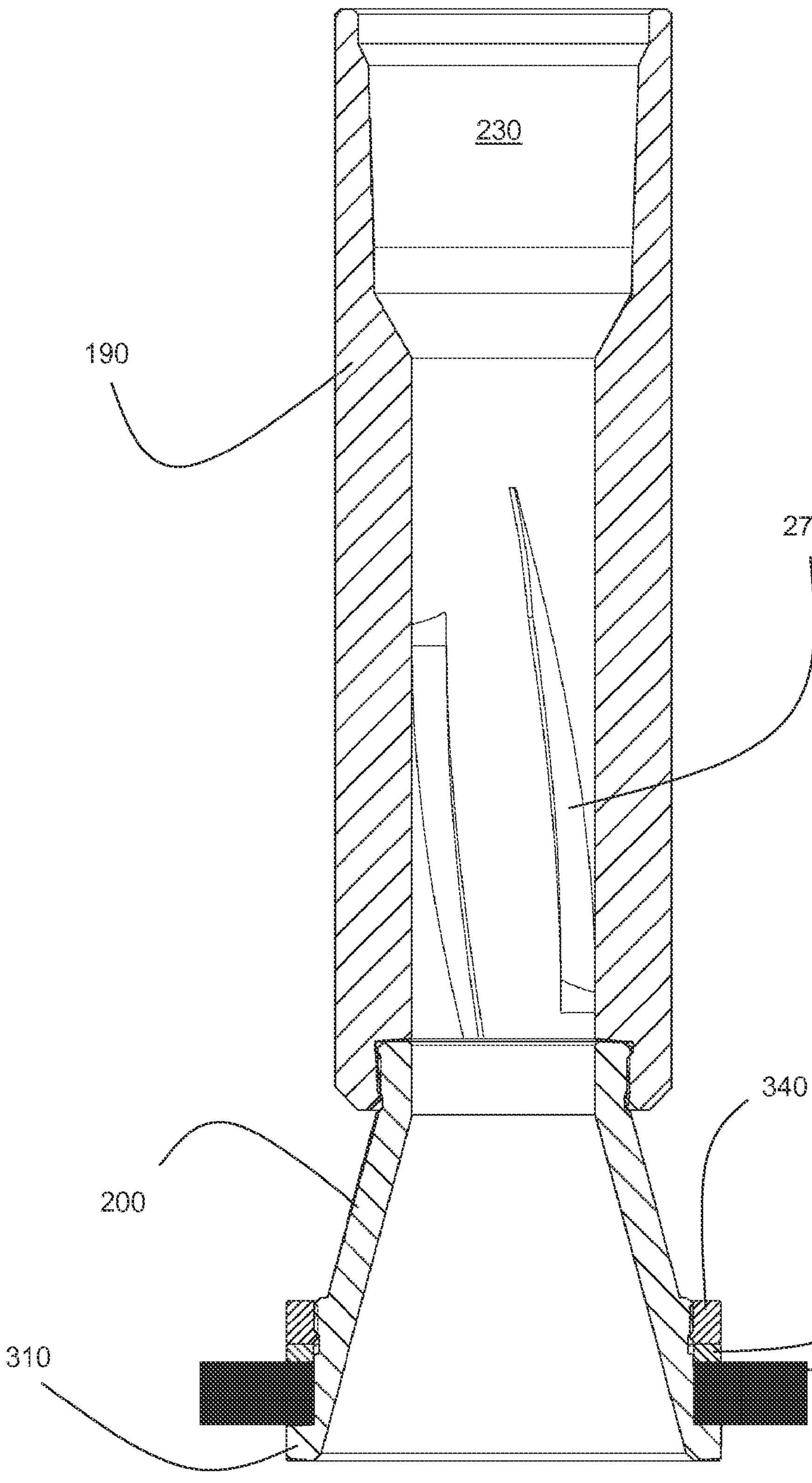
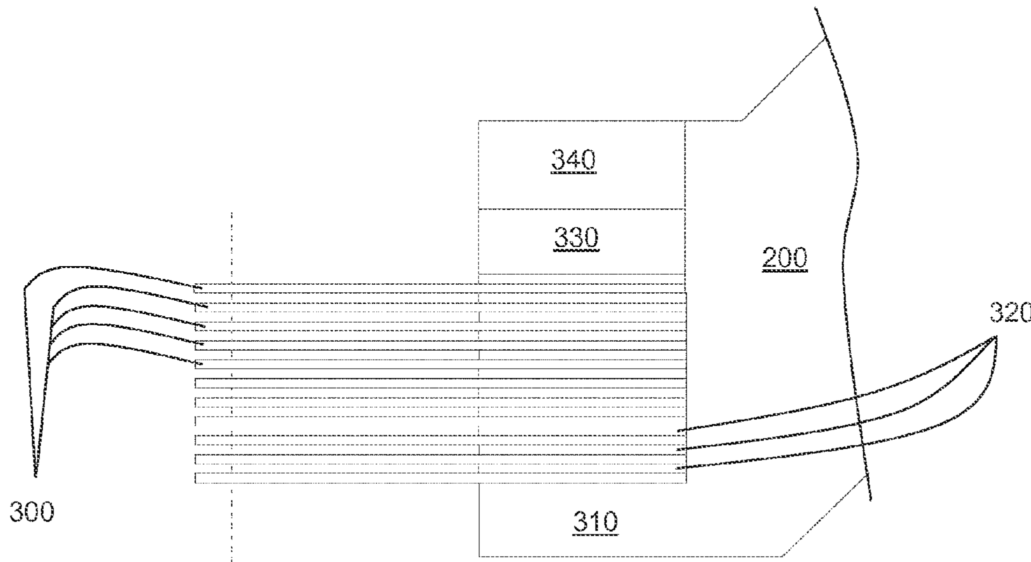



Fig. 6

*Fig. 7A*



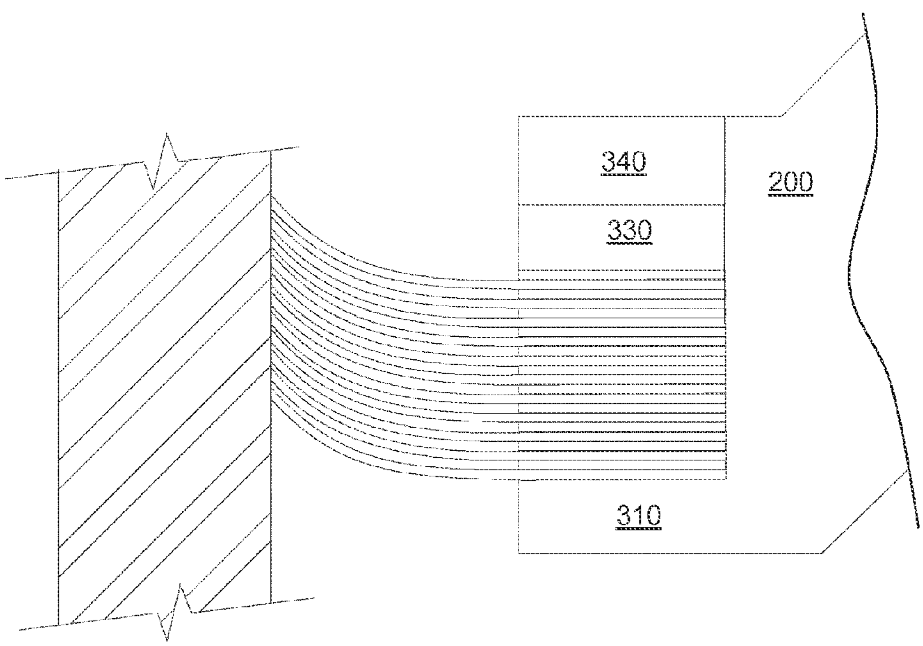




*Fig. 7B*

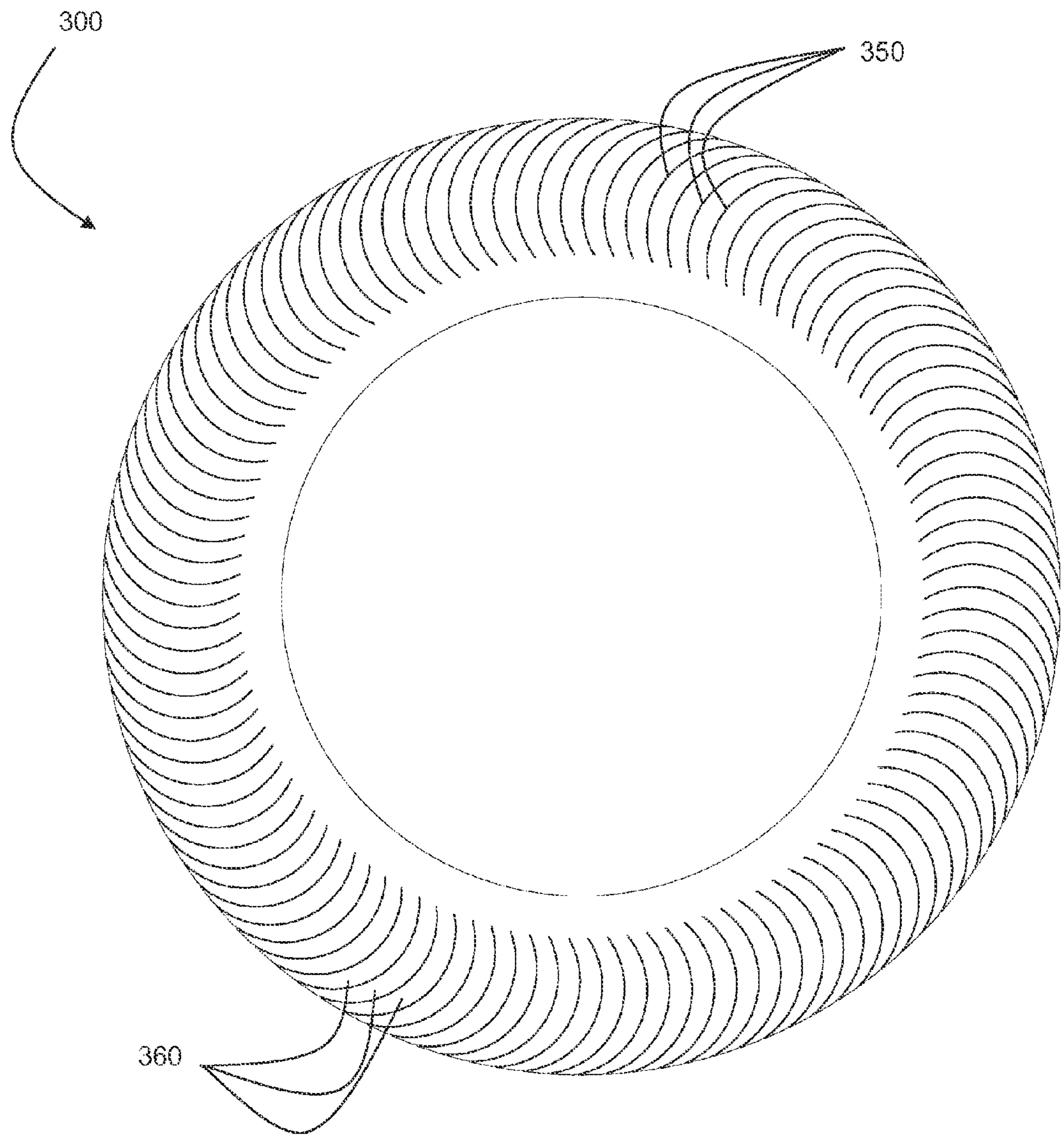



Fig. 8

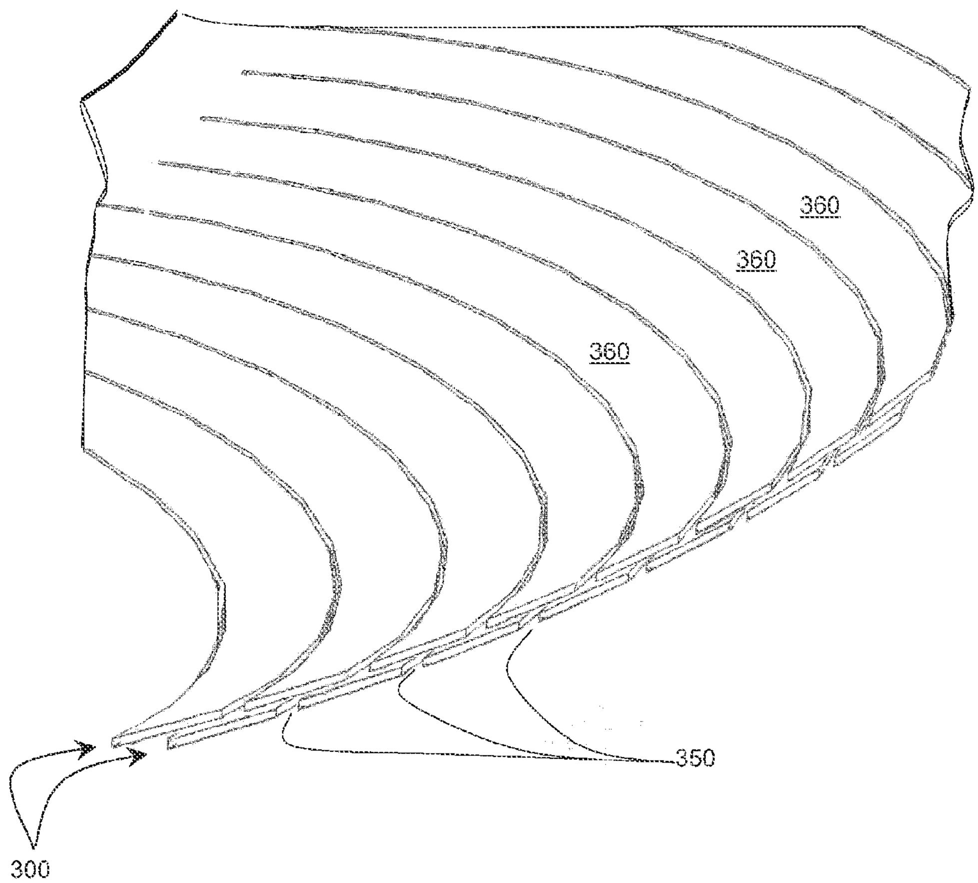



Fig. 9

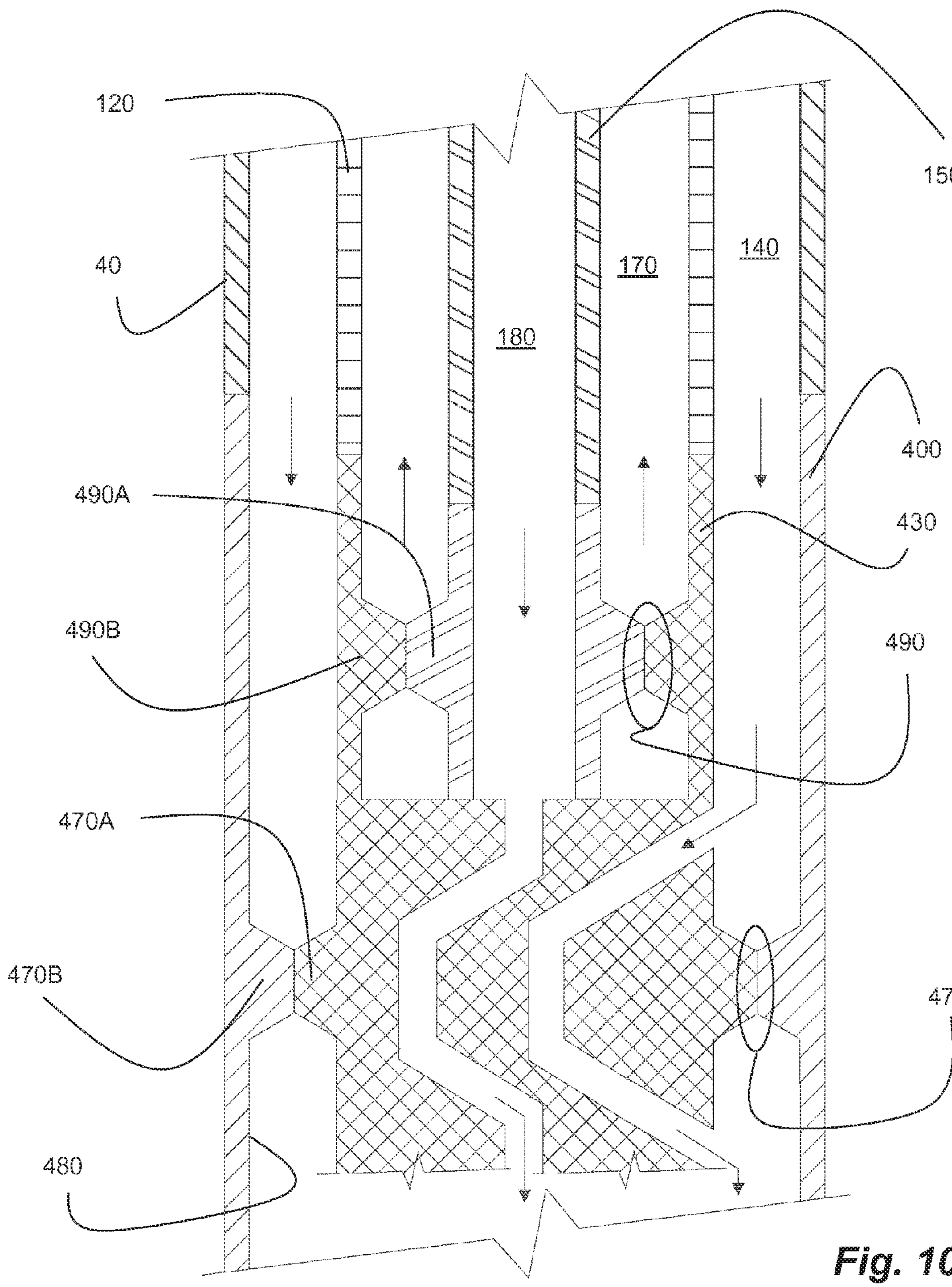



Fig. 10

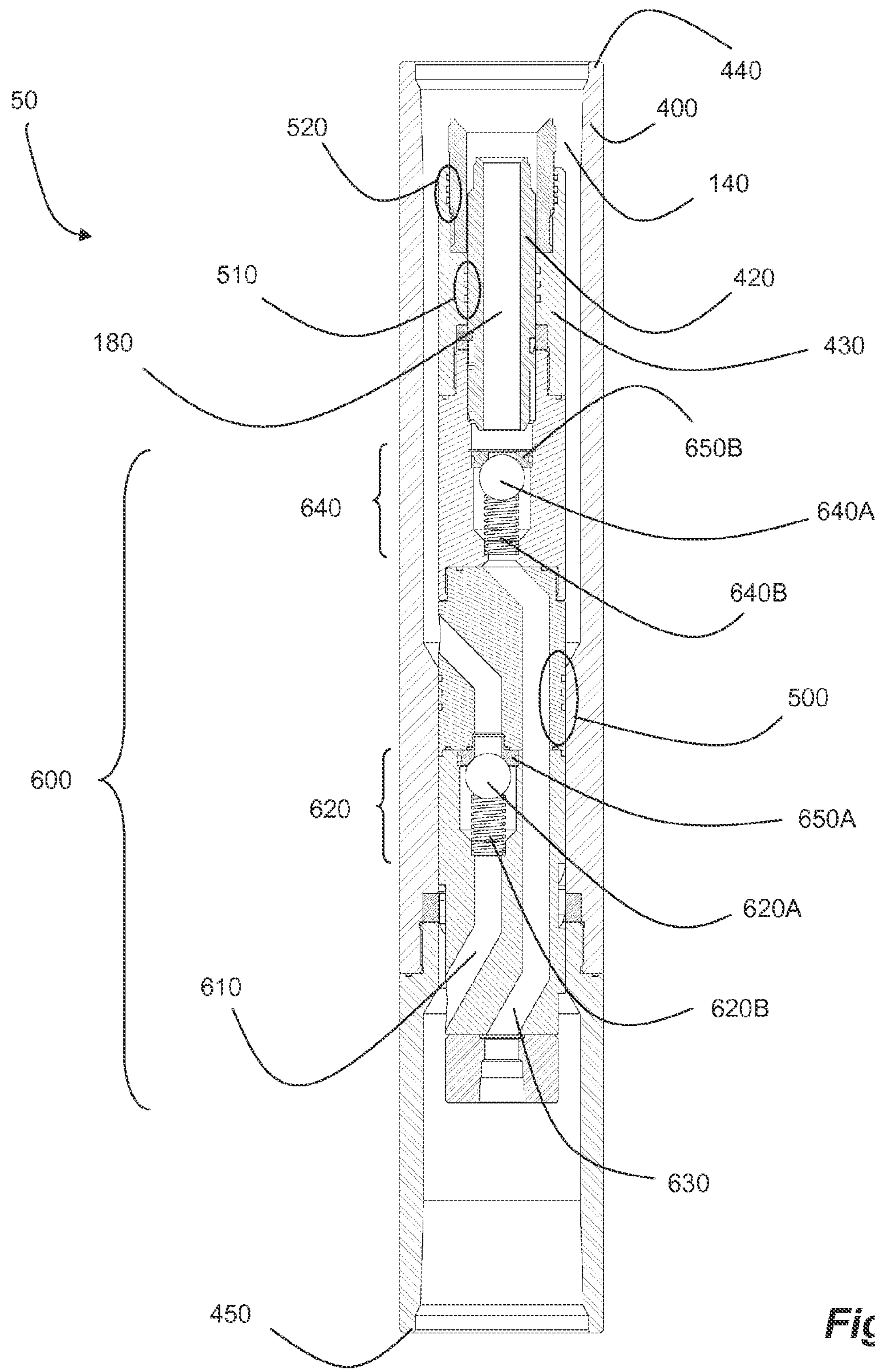

440
400
50
520
140
510
420
180
430
650B
640
640A
640B
500
600
620
650A
620A
610
620B
630
450

Fig. 11

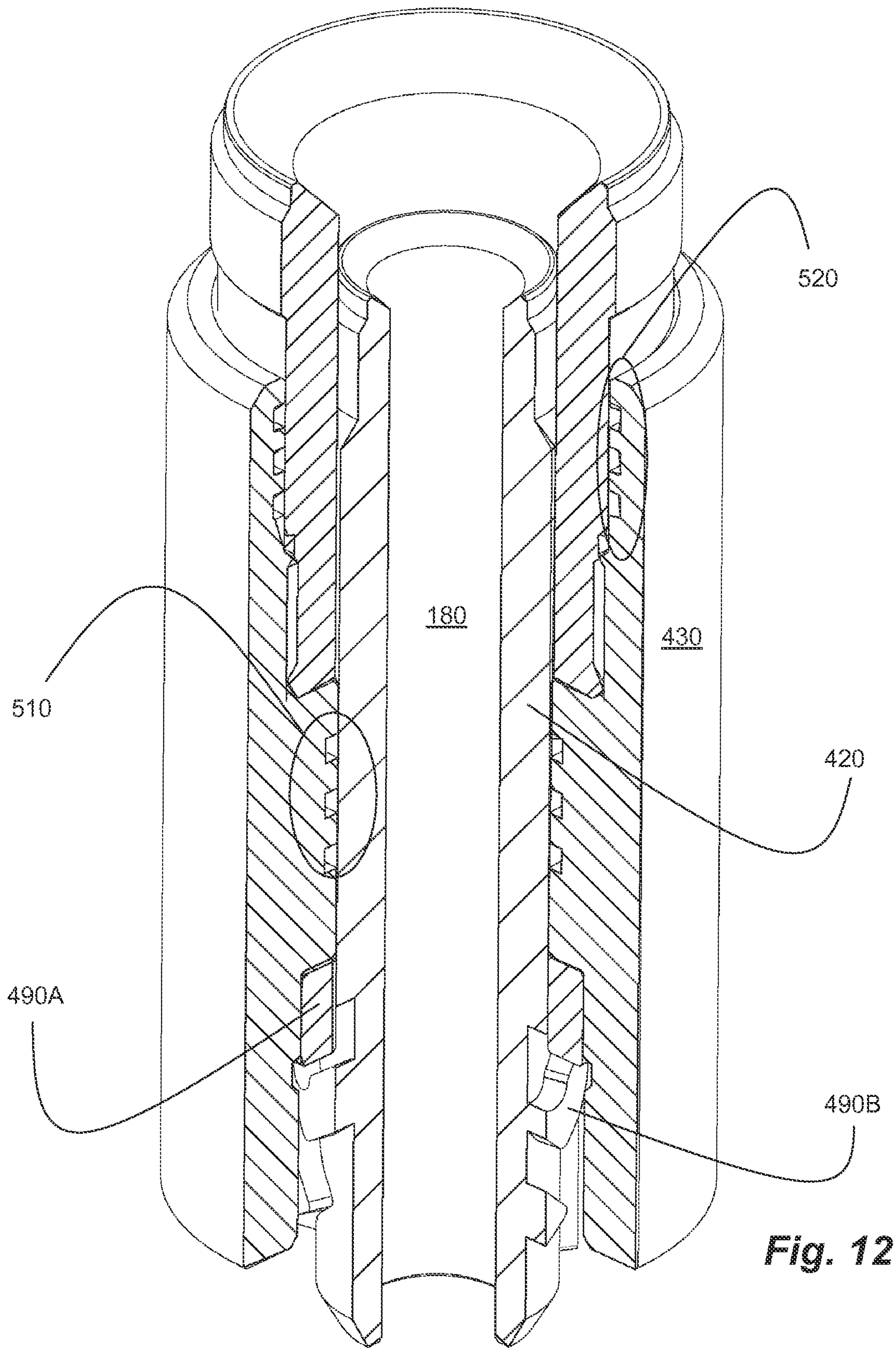



Fig. 12

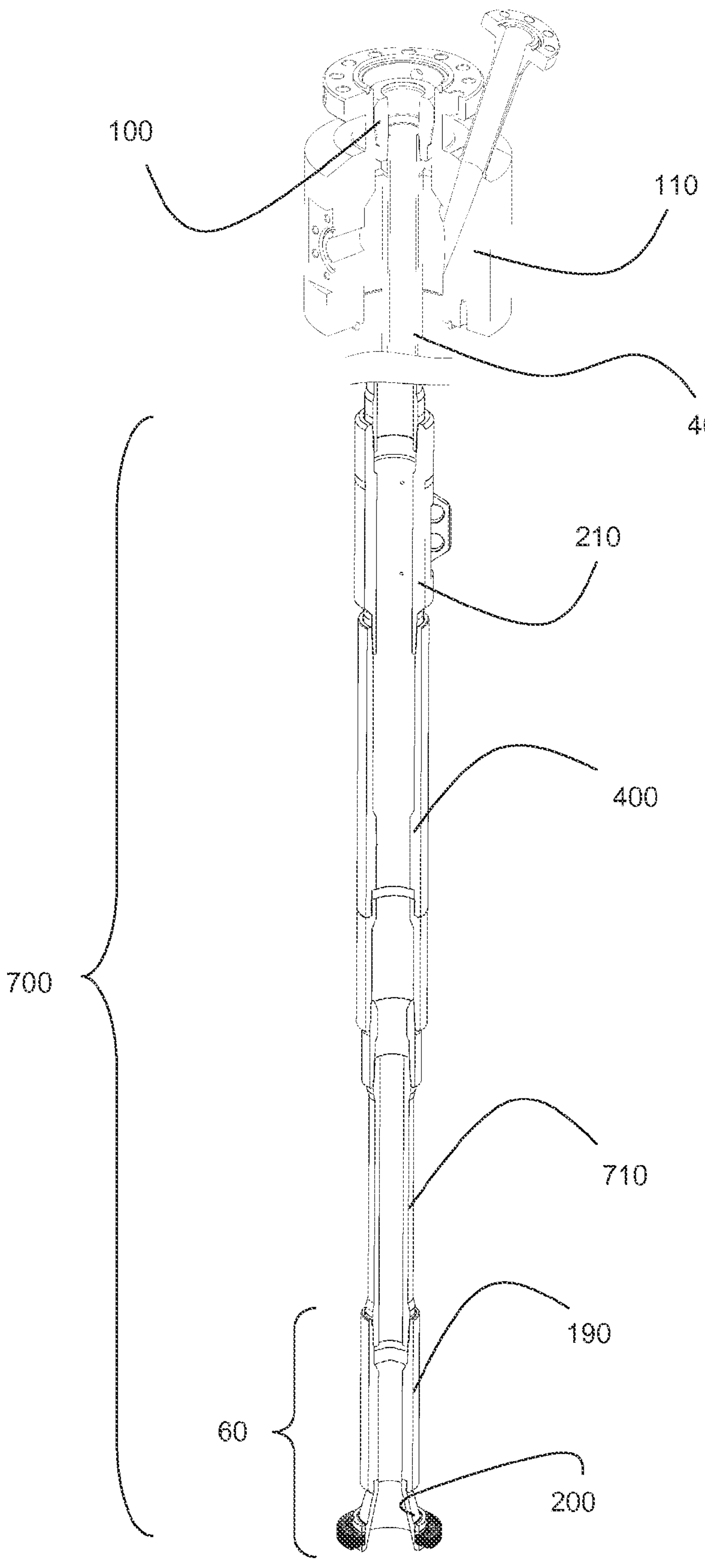



Fig. 13

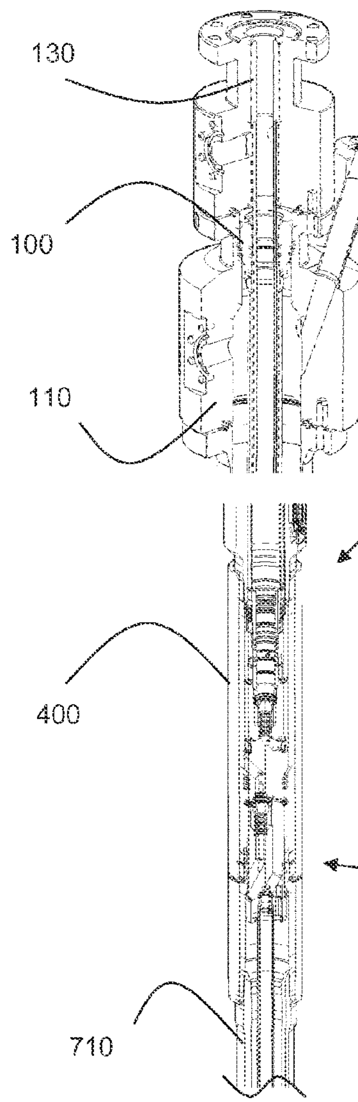



Fig. 14A

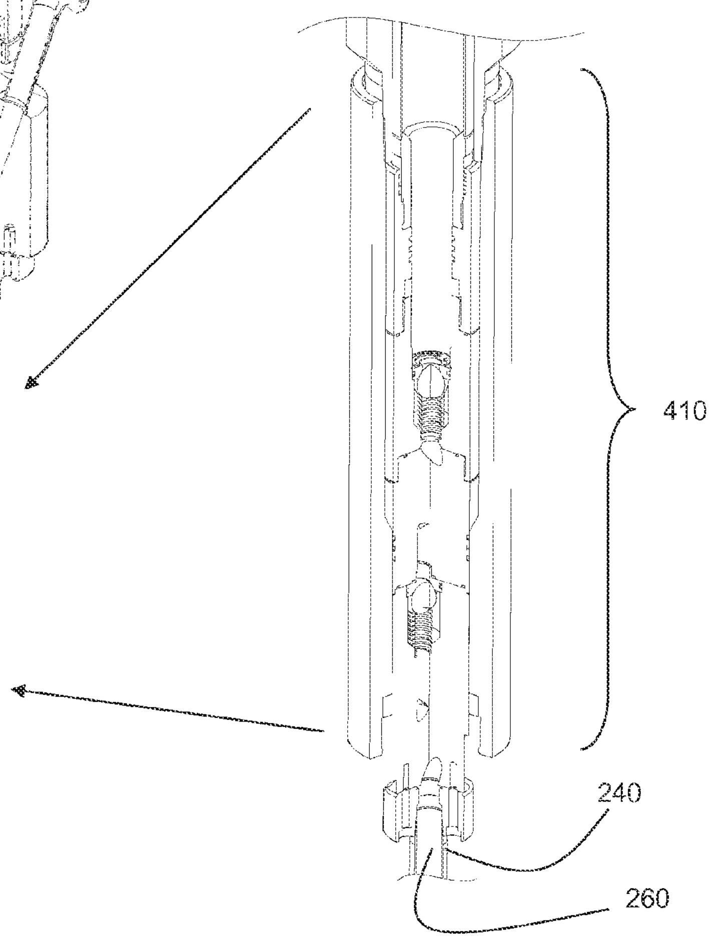



Fig. 14B

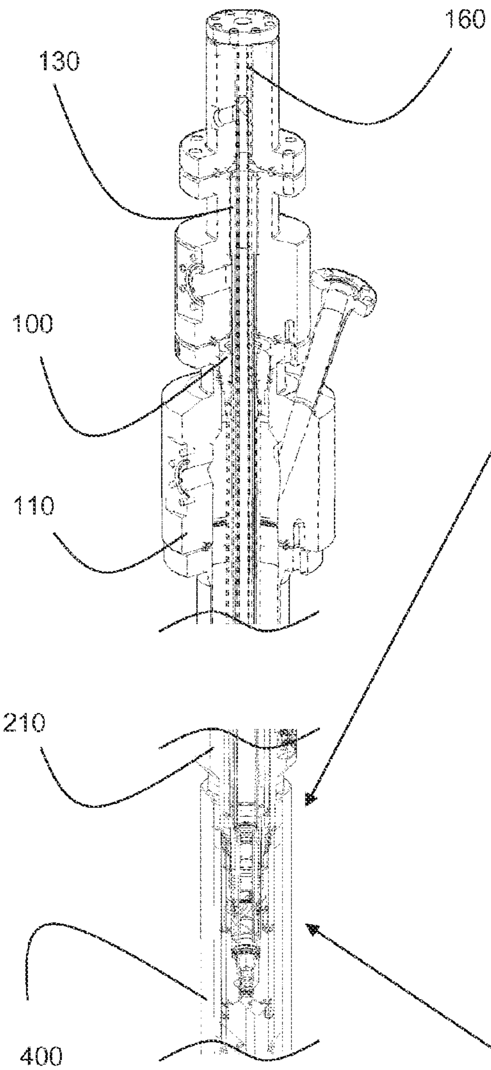



Fig. 15A

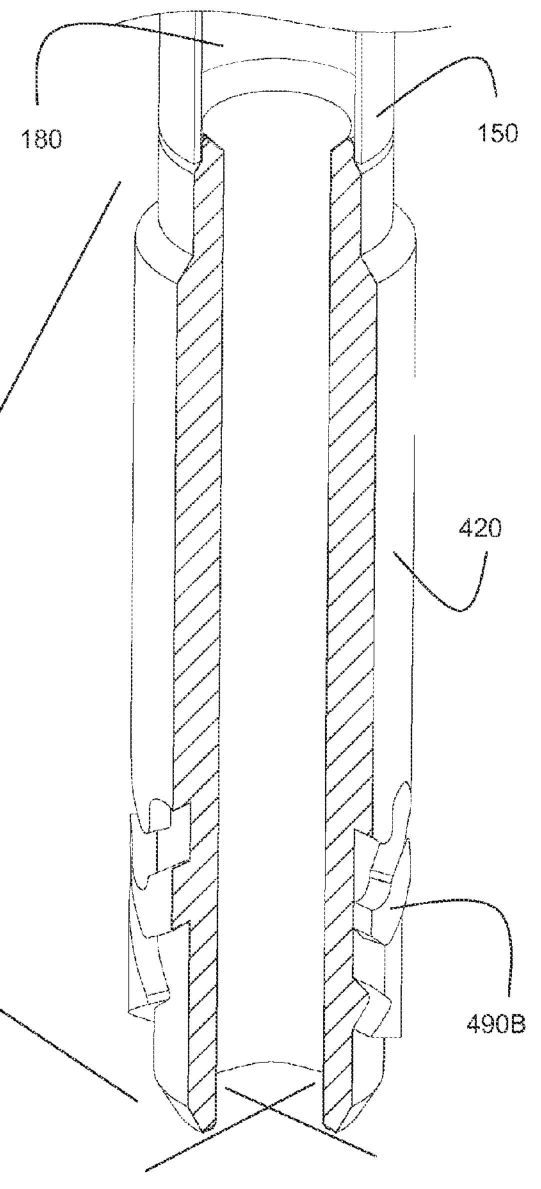



Fig. 15B

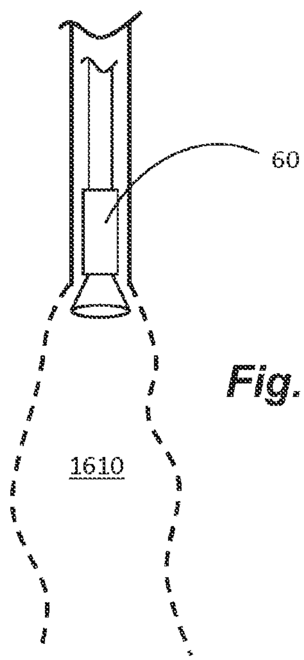



Fig. 16A

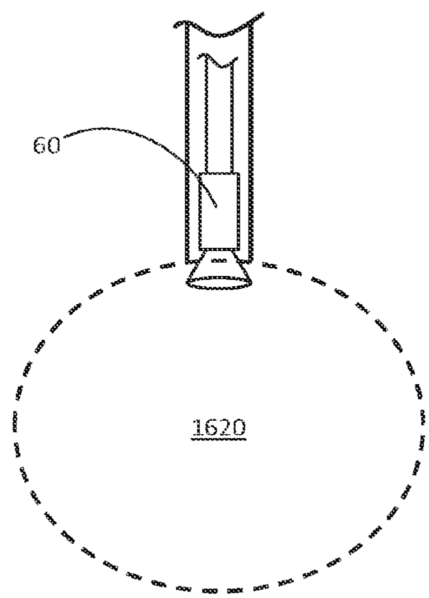



Fig. 16B

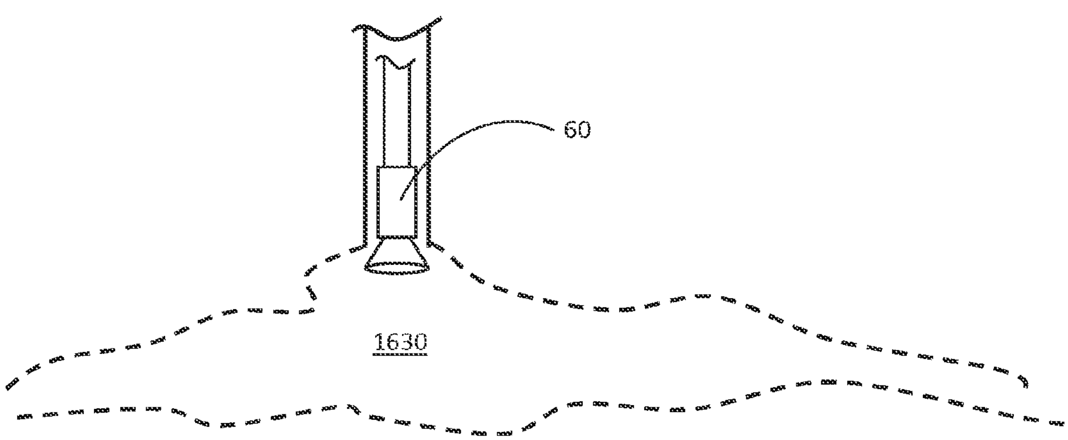



Fig. 16C

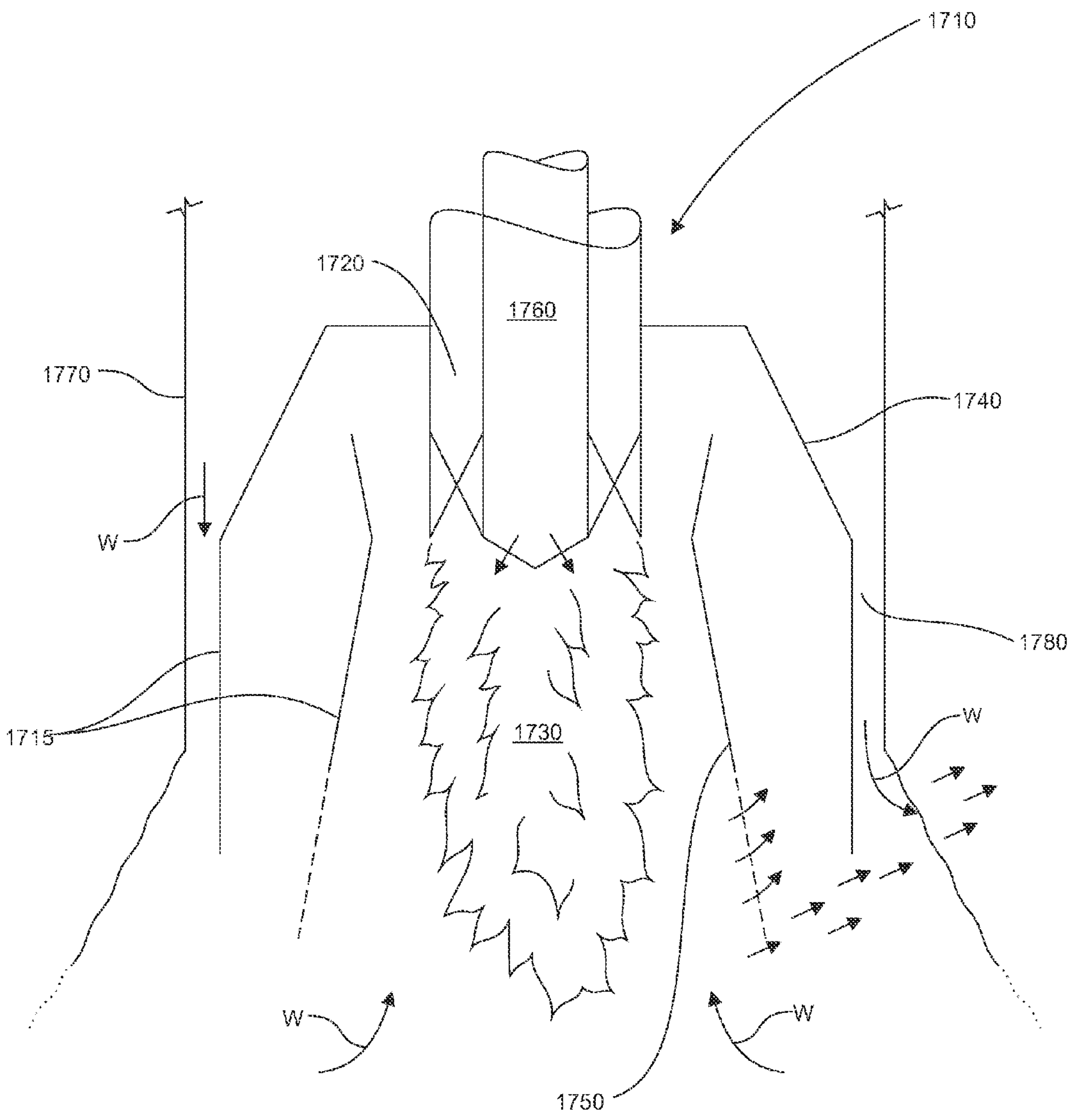



Fig. 17

# APPARATUS AND METHOD FOR DOWNHOLE STEAM GENERATION AND ENHANCED OIL RECOVERY

## CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part application that claims the benefits under 35 U.S.C. 120 of the U.S. patent application Ser. No. 12/687,711, filed on Jan. 14, 2010, and published as US 2010/0181069 on Jul. 22, 2010, the entirety of which is incorporated fully herein by reference.

This application further claims the benefits under 35 U.S.C 119(e) of the U.S. Provisional Application Ser. No. 61/560,468, filed Nov. 16, 2011, the entirety of which is also incorporated fully herein by reference.

## FIELD OF THE INVENTION

The present invention relates a method for creating a drive front in a target zone in a hydrocarbon reservoir for enhanced oil recovery. More specifically, a downhole burner is arranged to access a cavity in the target zone for creating hot gases which enter into the target zone. Water injected into the target zone forms a steam drive front hydrocarbon reservoir.

## BACKGROUND OF THE INVENTION

It is known to conduct enhanced oil recovery (EOR) of hydrocarbons from subterranean hydrocarbon formations after primary recovery processes are no longer feasible. EOR include thermal methods such as in-situ combustion, steam flood, and miscible flooding which use various arrangements of stimulation or injection wells and production wells. In some techniques the stimulation and production wells may serve both duties. Other techniques include steam flooding, cyclic steam stimulation (CSS), in-situ combustion and steam assisted gravity drainage (SAGD). SAGD uses closely coupled, a horizontally-extending steam injection well forming a steam chamber for mobilizing heavy oil for recovery at a substantially parallel and horizontally-extending production well.

Thermal methods of EOR can only be implemented in wells that have been completed for thermal completions. Due to the high temperatures used in thermal completions, wells employing such EOR techniques must be completed using materials, such as steel and cement, that can withstand high temperatures. Wells that were not completed with such high temperature resistant materials cannot implement thermal completions for EOR. Accordingly, well operators must decide on whether or not to implement of thermal EOR and based on this decision complete a well using (or not) high temperature resistant materials.

U.S. Pat. No. 3,196,945 to Forrest et al (assigned to Pan American Petroleum Company) discloses a downhole process comprising a first igniting a reservoir and then injecting air or an equivalent oxygen containing gas in an amount sufficient to create a definite combustion zone or front, the front being at high temperature, typically 800-2400° F. Called forward combustion, Forrest contemplates an oxygen rich front for continued combustion. Demands for large air flow is reduced by co-injection of water or other suitable condensable fluid into the heated formation to create steam front that urges the movement of hydrocarbons or oil. Forrest can co-discharge water and air to the heated formation for creating high temperature steam.



U.S. Pat. No. 4,442,898 to Wyatt (assigned to Trans-Texas Energy Inc.) discloses a downhole vapor generator or burner. High pressure water in an annular sleeve around the burner combustion chamber within which an oxidant and fuel are combusted. The energy from the combustion vaporizes the water surrounding the combustion chamber, cooling the burner and also creating high temperature steam for injection into the formation.

U.S. Pat. No. 4,377,205 to Retallick discloses a catalytic low pressure combustor for generating steam downhole. The steam produced from the metal catalytic supports is conducted to steam generating tubes, and the steam is injected into the formation. Any combustion gases produced are vented to the surface.

U.S. Pat. No. 4,336,839 to Wagner et al (assigned to Rockwell International corp.) discloses a direct firing downhole steam generator comprising an injector assembly axially connected with a combustion chamber. The combustion products, including $CO_2$, are passed through a heat exchanger where they mix with pre-heated water and are ejected out of the generator into the formation through a nozzle.

U.S. Pat. No. 4,648,835 to Eisenhawer et al. (assigned to Enhanced Energy Systems) discloses a direct fire steam generator comprising a downhole burner employing a unique ignition technique using the gaseous injection of a pyrophoric compound such as triethylborane. Natural gas is burned and water is introduced to control combustion. The combustion products, like in Wagner are mixed with water and the resulting steam and other remaining combustion products are injected into the formation.

US Patent Application Publication 2007/0193748 to Ware et al (assigned to World Energy Systems, Inc.) discloses a downhole burner for producing hydrocarbons from a heavy-oil formation. Hydrogen, oxygen and steam are pumped by separate conduits to the burner. A portion of the hydrogen is combusted and the burner forces the combustion products out into the formation. Incomplete combustion is useful in suppressing the formation of coke. The injected steam cools the burner, thereby creating a super heated steam which is also injected into the formation along with the combustion products. $CO_2$ from the surface is also pumped downhole for heating and injection into the formation to solubilise in oil for reducing its viscosity.

In-situ processes to date have not successfully provided economic solutions and have not resolved issues of temperature management, corrosion, coking and overhead associated with existing surface equipment.

## SUMMARY OF THE INVENTION

The present invention is an apparatus and method of creating a drive front in a hydrocarbon reservoir. The apparatus is positioned in a cased wellbore within a target zone in the hydrocarbon reservoir. The apparatus comprises a downhole burner fluidly connected to a tubing string extending downhole. The tubing string comprises a plurality of passages for at least fuel, and oxidant and water. The downhole burner creates a combustion cavity within the target reservoir zone by combusting the fuel and the oxidant, such as oxygen, at a temperature sufficient to melt the reservoir at the target zone or otherwise form a cavity below the downhole burner. Once the combustion cavity is created, the downhole burner operates at steady state for creating and sustaining hot combustion gases in the combustion cavity, which flow or permeate into the hydrocarbon reservoir. The hot combustion gases permeate away from the combustion cavity forming a gaseous drive front, transferring some of its heat to the rest of the reservoir.

Water is also injected into the target zone above the combustion cavity, which flow or permeate laterally into the reservoir adjacent the wellbore. In the reservoir, the water acts to cool the reservoir adjacent the wellbore, decreasing the amount of heat lost to the overburden. At an interface, the water and hot combustion gases combine to create a steam and gaseous drive front.

Further, the injection of water adjacent the wellbore also cools the cased wellbore, protecting the casing against the heat from the steam and hot combustion gases. Accordingly, the present invention is not limited to use only in thermally completed wells and can be implemented at any cased wellbore, whether or not the wellbore was completed for thermal EOR.

In a broad aspect of the invention, a process for creating a steam and gas drive front is disclosed. A downhole burner assembly, fluidly connected to a main tubing string, is positioned within a target zone in a hydrocarbon reservoir. The burner assembly creates a combustion cavity by combusting fuel and an oxidant at a temperature sufficient to melt the reservoir or otherwise create a cavity. The burner assembly then continues steady state combustion to create and sustain hot combustion gases for flowing and permeating into the reservoir for creating a gaseous drive front. Water is injected into the reservoir, uphole of the combustion cavity for creating a steam drive front.

In another broad aspect of the invention, a downhole steam generator for enhanced oil recovery from a hydrocarbon reservoir accessed by a cased and completed wellbore is disclosed. The downhole steam generator is a burner assembly positioned within the cased wellbore at the hydrocarbon reservoir, the burner assembly having a high temperature casing seal adapted for sealing a casing annulus between the downhole burner and the cased wellbore, and a means for injecting water into the hydrocarbon reservoir above the casing seal. The high temperature casing seal can pass through casing distortions, and is reusable, not being affected substantially by thermal cycling.

In another broad aspect of the invention, a system for creating a drive front in a hydrocarbon reservoir having a cased wellbore is disclosed. The system has a burner assembly having a downhole burner and a high temperature casing seal for sealing a casing annulus between the downhole burner and the casing of the cased wellbore. The high temperature casing seal can pass through casing distortions and is reusable, substantially not being affected by thermal cycling.

In another broad aspect of the invention, a system is provided for fluidly connecting three concentric passageways in a main tubing string to a downhole tool. The system has an outer housing, an intermediate mandrel and an inner mandrel. The outer housing is releaseably connected to the intermediate mandrel by an intermediate latch assembly and similarly, the inner mandrel is releaseably connected to the intermediate mandrel by an inner latch assembly. The intermediate mandrel is fit within the outer housing, forming an intermediate annulus therebetween, and is adapted to fluidly connect to an intermediate tubing string. The inner mandrel is fit within the intermediate mandrel, forming an inner annulus therebetween and is adapted to fluidly connect to an inner tubing string. The inner mandrel further has an inner bore.

In another broad aspect, a process for creating a drive front in a hydrocarbon reservoir for enhanced oil recovery is provided comprising arranging a burner assembly in a wellbore to access a cavity in a target zone in the hydrocarbon reservoir and directing combustion from the burner assembly into the cavity and sustaining hot combustion gases therein, the hot combustion gases entering into and permeating from the cavity to the heat the target zone. The process further comprises injecting water into the target zone, the water entering into and permeating into the target zone and interacting with the hot combustion gases therein for creating steam in the target zone, and forming a steam drive front in the hydrocarbon reservoir.

In another aspect, the cavity can be artificially created including mechanical, hydraulic or combustion operations or may be pre-existing, having been formed due to prior reservoir operations or be naturally occurring.

## BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a side cross-sectional view of an embodiment of the present invention, illustrating a combustion cavity in a hydrocarbon reservoir, the cavity being created by downhole burner and formed for disseminating hot combustion gases for forming a gaseous drive front and interacting with water injected uphole of the cavity for forming an additional steam drive front;

FIG. **2**A is a side quarter-sectional view of a wellhead for supporting three tubing strings extending down a cased wellbore according to one embodiment of the present invention;

FIG. **2**B is a side quarter-sectional elevation of the three tubing strings of FIG. **2**A (casing omitted) and illustrating a main tubing string supporting the downhole burner at a burner interface assembly, the main tubing string having an intermediate and an inner tubing string disposed therein;

FIG. **3** illustrates a quarter-sectional, perspective view across the casing and three concentric tubing strings;

FIG. **4** is a side quarter-sectional view of an embodiment of a downhole burner sealed at a downhole end to a casing for fluidly connecting a casing annulus and the reservoir through perforations;

FIG. **5** is a side, quarter-sectional view of the burner of FIG. **3** with the casing omitted, and illustrating the fuel passageway, the oxygen passageway and the nozzle;

FIG. **6** is a side, quarter-sectional view of the burner of FIG. **3** with the casing and oxygen passageway omitted for illustrating the casing seal and an embodiment of fuel passageway swirl vanes;

FIG. **7**A is a partial cross-sectional view of the nozzle and an embodiment of a brush-type casing seal of FIG. **3** with the casing omitted;

FIG. **7**B illustrates an activated brush seal according to FIG. **7**A and showing the stack of flexible brush rings flexing when constrained by the casing;

FIG. **8** is a overhead plan view of one concentric brush ring of a stack of concentric brush rings of a brush seal and an arrangement of spiral slits and fingers;

FIG. **9** is a perspective view of two brush rings of the stack of concentric brush rings according to FIG. **8** illustrating a rotational offsetting of the spiral slits for forming a tortuous, restrictive fluid path therethrough;

FIG. **10** is a schematic representation a main tubing string, an intermediate tubing latched within the bore of the main tubing string, and an inner tubing latched and terminated within the bore of the intermediate tubing, three fluid passageways created therein, the inner annulus being terminated at the intermediate mandrel;

FIG. **11** is a cross-sectional view of the burner interface assembly illustrating the outer housing, the intermediate and inner mandrels, the intermediate and inner latch assemblies, and the backpressure valve assembly;

FIG. **12** is a side quarter-sectional view of an uphole end of the intermediate mandrel for illustrating termination of the inner and intermediate tubing and the inner mandrel having an inner tubing latch;

FIG. **13** is a quarter-sectional and elevation view of a step of the running in of an embodiment of the apparatus of the invention, more particularly illustrating the main tubing hanger, and downhole adjacent the reservoir, a torque anchor, outer housing, pup joint, burner housing, burner nozzle and casing seal;

FIG. **14**A is a quarter-sectional and elevation view of a further step according to FIG. **13**, more particularly illustrating the insertion of the intermediate tubing string, hanging the tubing from an intermediate tubing hanger, latching of the intermediate mandrel and positioning of the oxygen passageway within the burner housing;

FIG. **14**B is a closeup of the burner interface assembly of FIG. **14**A for illustrating the intermediate tubing, the intermediate mandrel and the oxygen passageway;

FIG. **15**A is a quarter-sectional and elevation view of a further step according to FIG. **13**, more particularly illustrating the insertion of the inner tubing string, hanging the inner tubing from an inner tubing hanger, latching of the inner mandrel;

FIG. **15**B is a closeup of the burner interface assembly of FIG. **15**A for illustrating the hanging the inner tubing from the inner tubing hanger, the inner tubing and the inner mandrel;

FIG. **16**A is a schematic representation of an embodiment of a burner assembly accessing a cavity created artificially by reaming;

FIG. **16**B is a schematic representation of an embodiment of a burner assembly accessing a cavity created artificially by hydraulic washing;

FIG. **16**C is schematic representation representative drawing of an embodiment of a burner assembly accessing a preexisting cavity; and

FIG. **17** is a schematic representation of a burner assembly fit with a shroud disposed at a downhole end thereof and receiving injected water thereabout.

## DETAILED DESCRIPTION OF THE INVENTION

As shown in FIG. **1**, a thermal process utilizes a downhole production of heat, steam and hot combustion gases (primarily CO, $CO_2$, and $H_2O$) to best effect for the recovery of residual or otherwise intractable hydrocarbons from a hydrocarbon reservoir **10**. A burner assembly **20** initially creates a combustion cavity **30** and then creates and sustains the creation of hot combustion gases, such as CO, $CO_2$, and $H_2O$. Addition of water to the reservoir **10** above the combustion cavity **30** results in the production of a steam drive front. The steam and hot combustion gases combine to create a steam and gaseous drive front.

With further reference to FIGS. **1**, **2**B, **3**, **4** and **13**, apparatus for implementing such a process comprises a burner assembly **20** at a downhole end of a main tubing string **40** and one or more additional tubing strings. The main tubing string **40** and other tubing strings form a plurality of discrete fluid passageways for supplying the burner assembly **20**. As shown in FIG. **4**, the downhole burner **60** is terminated in an existing cased wellbore adjacent casing perforations accessing the reservoir **10**. The burner assembly **20** can comprise a burner interface assembly **50** for fluidly connecting to the tubing strings, a downhole burner **60**, and a casing seal **70** for sealing a casing annulus **80** between the downhole burner **60** and a casing **90** of the cased wellbore. The casing annulus **80** is yet another passageway used for directing water from the casing annulus **80** to the reservoir **10**.

As shown in FIGS. **2**A to **4**, one approach is to suspend the burner assembly **20** from a conventional sectional tubing string supported by a conventional tubing hanger **100** on a wellhead **110**. The casing annulus **80** is formed between the casing **90** of the wellbore and the main tubing string **40** and extends to the annular space between the casing **90** of the wellbore and the burner assembly **20**.

An intermediate tubing string **120** having an intermediate bore, such as an intermediate coil tubing string, is supported by an intermediate tubing hanger **130** on the wellhead **110** and disposed within a bore of the main tubing string **40**. An intermediate annulus **140** is formed between the main tubing string **40** and the intermediate tubing string **120**.

An inner tubing string **150**, such as an inner coil tubing string, is supported by an inner tubing hanger **160** on the wellhead **110** and is further disposed within the intermediate bore of the intermediate tubing string **120**, forming a inner annulus **170** therebetween. The inner tubing string **150** further has an inner bore **180**.

The wellhead **110** and tubing hangers **100**, **130**, **160** can be any appropriate wellhead and tubing hangers that are commonly available in the industry, such as the thermal wellhead and tubing hangers commercially available from StreamFlo Industries, Ltd., located at Edmonton, Alberta, Canada. The casing annulus **80**, the intermediate annulus **140**, inner annulus **170**, and the inner bore **180** all define discrete passageways for supplying the burner assembly **20**.

The casing **90** of the cased wellbore, main tubing string **40**, the intermediate tubing string **120** and the inner tubing string **150**, creating the four discrete passageways, terminate at the burner interface assembly **50**. The casing annulus **80** terminates at the downhole burner **60** for communication with the reservoir **10**. The inner annulus **170** terminates at the burner interface assembly **50**. The two remaining discrete passageways, the intermediate annulus **140**, and inner bore **180**, all connect or terminate at the downhole burner **60**.

In one embodiment, the downhole burner **60** implements at least two fluid passageways for conducting fuel and oxidant for combustion. The oxidant is a source of oxygen, conventionally air, or more concentrated source such as a purified stream of oxygen. In a preferred embodiment, purified oxygen is used as the oxidant instead of conventional air, as conventional air produces combustion gases having a substantial amount of gaseous nitrogen products.

The burner interface assembly **50** fluidly connects two of the discrete passageways to two fluid passageways of the downhole burner **60**. In one arrangement, a third discrete passageway can be utilized as an isolating passageway between the fuel and the oxygen for sensing or detecting leaks in the discrete passageways for the fuel and oxygen.

The downhole burner **60** comprises a burner housing **190** having a downhole portion **200** for the mixing of fuel and oxygen. The burner housing **190** supports a high temperature casing seal **70** for sealing the casing annulus **80** from the combustion cavity **30**. The sealed casing annulus **80** can be used to fluidly communicate water down to the target zone, which is then injected into the reservoir **10** for creating steam within the target zone, above the combustion cavity **30**.

With reference to FIGS. **2**A, **2**B, and **3**, one embodiment of the present invention comprises the burner assembly **20** fluidly connected to the main tubing string **40**. A downhole burner **60** is positioned at a downhole portion of a cased portion of an injection well, the casing **90** being perforated into the reservoir **10**. The main tubing string **40** extends downhole and has conduits or passageways for conducting or transporting each of fuel, and oxygen, to the downhole burner **60**. For ease of installation, intermediate and inner tubing strings **120**, **150** are releasably connected to the burner assembly **20**.

The downhole components, or as part of the burner assembly **20**, can further comprise a torque anchor **210** to set the main tubing string **40** in the casing **90**.

In greater detail, and with reference to FIGS. **3** to **6**, the burner housing **190** is adapted at an uphole portion **220** for fluid communication with the intermediate annulus **140** and inner bore **180**. In one embodiment, the burner housing **190** is fluidly connected to the intermediate annulus **140** and the inner bore **180** through the burner interface assembly **50**. The burner housing **190** comprises two fluid passageways for fluidly communicating the fuel and oxygen.

As best shown in FIGS. **5** and **6**, the burner housing **190** comprises the downhole portion or burner nozzle **200** for combustion of the fuel and oxygen and an uphole portion **220** defining the two fluid passageways for fluidly communicating the fuel and oxygen to the nozzle **200**. The uphole portion **220** has a bore **230** and a concentric conduit or tubing **240** extending therethrough for creating the two fluid passageways. A fuel passageway **250** is defined by the annular space formed between the bore **230** and the concentric conduit **240**. The concentric conduit **240** further has a bore defining an oxygen passageway **260**.

The fuel passageway **250** is adapted to fluidly communicate with the intermediate annulus **140**, communicating fuel from the surface to the nozzle **200**. The bore **230** of the burner housing **190** and the fuel passageway **250** open into the nozzle **200** for injecting the fuel into the nozzle **200**. The fuel passageway **250** can further have fuel swirl vanes **270** for aiding in the mixing of the fuel and oxygen.

The oxygen passageway **260** is in fluid communication with the inner bore **180**, communicating oxygen from the surface to the nozzle **200**. The oxygen passageway **260** has an opening **280** at a downhole end for injecting oxygen into the nozzle **200**. The oxygen passageway **260** can further have oxygen swirl vanes (not shown) for aiding in the mixing of the fuel and oxygen. The oxygen and fuel mix for combustion at the nozzle **200**.

With reference to FIG. **5**, as stated above, the fuel passageway **250** can further have fuel swirl vanes **270** for imparting a rotation to the fuel being injected into the nozzle **200**. The oxygen passageway **260** can also have oxygen swirl vanes for imparting a rotation, counter to the direction of the rotation of the fuel, for maximizing the mixing of the fuel and oxygen for increasing the efficiency of the combustion of the fuel and oxygen. In a preferred embodiment, the ratio of swirl velocity to axial flow velocity of either the fuel or oxygen is substantially 1:2.

In an alternate embodiment, the opening **280** of the oxygen passageway **260** can be fitted with a bluff body (not shown) to reduce the axial momentum of the oxygen for stabilizing the combustion flame.

Further, in another alternate embodiment (not shown), the burner housing **190** can have two side-by-side bores extending therethrough for forming the fuel passageway and the oxygen passageway. Each bore can have an opening at a downhole end for injecting the fuel and oxygen into the nozzle **200** for combustion.

Conventional burner discharge arrangements can be employed including utilizing a plurality of orifices and concentric discharges. The nozzle **200** can be any open ended tubular structure that allows mixing and combustion of the fuel and oxygen. As shown, the nozzle **200** is a typical inverted truncated frusto-conical nozzle. The truncated apex is fluidly connected to the burner housing **190** and the nozzle **200** extends radially outwardly towards a downhole end.

As shown in FIGS. **4** and **6**, the high temperature casing seal **70** can be located on the downhole burner **60** to isolate the casing annulus **80** from the combustion cavity **30**. Accordingly, the casing seal **70** is generally located low on the downhole burner **60**, such as between the downhole portion of the burner housing or nozzle **200** and the casing **90**. In alternate embodiments (not shown), the casing seal **70** can located between the uphole portion **220** of the burner housing **190** and the casing **90**.

Often, cased wellbores have casing distortions or kinks which introduce challenges to installation and tolerances for related seals to the casing. The casing distortions are an abrupt shifting of the casing axis resulting in a casing portion that is narrower than a nominal inner diameter of a typical casing. The passage of seals and other downhole tools are difficult at best if the nature of the seal is to initially comprise an outer diameter of seal which is larger than the inner diameter of casing and certainly greater than the distortion. Although downhole tools generally can be manufactured to have a small outer diameter to allow them to pass through a majority of distortions, seals generally can not. Seals having small outer diameter, although capable of passing through the distortions, are unlikely to fully seal against the casing downhole of the distortion where the casing again has a nominal inner diameter. Seals must also be able to withstand the extreme heat conditions created by a downhole burner when combusting the fuel and oxygen.

With reference to FIGS. **6** to **9**, an embodiment of the casing seal **70** is a brush-type seal comprising a plurality of flexible, concentric, metallic brush rings **300** stacked one on top of another. As best shown in FIGS. **6**, **7**A and **7**B, the brush rings **300** are stacked one on top of another upon a circumferential stop shoulder **310** at a downhole end of the nozzle **200**. Spacer rings **320** can be provided to alternate between the brush rings **300**. The stack of brush rings **300** and spacer rings **320** is secured in place by a compression ring **330** exerting an axial securing force to sandwich the rings **300**, **320** to the stop shoulder **310**. A compression nut **340** secures the compression ring **330**.

As shown in FIGS. **8** and **9**, each seal ring **300** has a multiplicity of slits **350** that are formed radially inward from an outer circumference of the seal ring **300** and which terminate before an inner diameter of the seal ring **300** for forming a plurality of flexible fingers **360**. The fingers are separated at the outer circumference and connected at the inner diameter. An inner most radial extension of each slit **350** defines the inner diameter of the multiplicity of slits **350** and is substantially the same as the outer diameter of the spacer rings **320**. The plurality of fingers **360**, flexing from the inner diameter, provide dimensional variability through flexibility for each concentric seal ring **300**.

Each slit **350** extends radially outwardly in a generally clockwise direction as viewed looking downhole. This particular slit arrangement or design is advantageous when removing and pulling up the casing seal **70**. In the event that the casing seal **70** becomes stuck, the clockwise slit arrangement allows the casing seal to be rotated in a counter-clockwise direction, thus decreasing the outer diameter of the casing seal **70**, and allowing it to dislodge from the casing **90**.

As shown in FIG. **9**, each seal ring **300** can be rotationally indexed relative to each adjacent seal ring **300**. While enabling radial flexibility, the slits **350** provide an avenue for fluids to leak therethrough. In order to minimize the amount of leaking of fluids through the slits **350**, each seal ring **300** is rotated such that the slits **350** of axially adjacent brush rings

300 are rotationally offset or misaligned. To further mitigate leakage through the slits 350, the plurality of concentric brush rings 300 are stacked. Each finger 360 of one seal ring 300 overlaps each finger 360 of an adjacent seal ring 300, for forming a tortuous axial path for restricting flow of casing annulus fluids therethrough.

Referring back to FIG. 7A, the brush seal 70 has an outer diameter greater than a nominal inner diameter of a casing 90 in a cased wellbore as indicated by the dashed line. The greater outer diameter defines the effective sealing diameter of a particular brush seal. Brush-type seals having differing effective sealing diameters can be readily installed depending on the size of the casing 90 in the cased wellbore.

When the brush-type seal is run downhole, each finger 360 of each seal ring 300 flexes uphole, reducing the overall outer diameter and conforming to the casing 90, while maintaining the effective sealing diameter. The reduction of the overall outer diameter of the brush rings 300 allow the brush seal 70 to pass through a cased wellbore during installation and pass by most casing distortions. Upon encountering a casing distortion, the ring fingers 360 of each concentric seal ring 300 can elastically flex an additional amount to enable movement past the distortion.

In an alternate embodiment, other casing seals might be employed including a metallic inflatable packer, such as those now introduced by Baker Oil Tools, as presented in a paper entitled "Recent Metal-to-Metal Sealing Technology for Zonal Isolation Applications Demonstrates Potential for Use in Hostile HP/HT Environments", published as SPE 105854 in February 2007. Such inflatable packers are small enough in diameter to also pass through casing distortions and may be able to withstand the extreme heat conditions created by the burner. However, such packers can be damaged by thermal cycling and may not be reusable.

For example, in a 7 inch (178 mm) casing having an inner diameter of about 164 mm, a burner bottom hole assembly (BHA) fluidly connected to the downhole end of a 3½ inch (89 mm) tubing, can be placed in a cased wellbore having the typical casing distortions. The burner BHA, comprising the burner interface assembly, pup joint, and downhole burner, had a total length of about 5 feet (1524 mm). A 2⅜ inch (60 mm) intermediate coil tubing was disposed within the 3½ inch (89 mm) tubing, and a 1¼ inch (32 mm) inner coil tubing was disposed within the intermediate coil tubing. The burner interface assembly was about 708 mm long and had an outer diameter of about 114 mm, while the burner housing was about 304 mm long with an outer diameter of about 93 mm. The brush seal had an outer diameter of about 164 mm and was installed on a nozzle having a circumferential shoulder of about 120 mm. Each brush ring and spacer ring had a thickness of about 0.25 mm. The pup joint, tailored to this particular example, was about 508 mm long and had an outer diameter of about 2⅞ inches (73 mm).

With reference to FIGS. 3 and 10, the fluid passageways can be formed by a series of tubing strings disposed in the bore of a larger tubing, or sectional tubing. Alternatively, two or more tubing strings might be arranged side-by-side (not shown). As shown in FIG. 3, the main tubing 40 is run down the cased wellbore forming the casing annulus 80 or a first casing annular fluid passageway therebetween. The intermediate tubing string 120 is disposed concentrically within the bore of the main tubing string 40, forming the intermediate annulus 140 or a second intermediate annular fluid passageway therebetween. The inner tubing string 150 is further disposed concentrically within the intermediate bore of the intermediate tubing string 120 forming the inner annulus 170 or a third inner annular fluid passageway therebetween. The bore of the inner tubing string 150 further defines the inner bore 180 or a fourth, inner bore fluid passageway.



Those skilled in the art would understand that although the intermediate tubing string 120 is concentrically disposed with the bore of the main tubing 40, the intermediate tubing string 120 may not remain concentrically aligned within the bore of the main tubing 40 as the intermediate tubing string 120 is run downhole. Similarly, the inner tubing string 150, although concentrically disposed in the intermediate bore of the intermediate tubing string 120 may not remain concentrically aligned as the inner tubing string 150 is run downhole.

In a basic form, two passageways are used for providing fuel and oxygen to the burner. A third passageway can be provided for isolating the fuel and oxygen, and even more favourably for acting as a sensing passageway for determining development of a leak therebetween.

With reference to FIGS. 10 to 12, in one embodiment, a burner interface assembly 50 fluidly connects three passageways of the main tubing 40 to the fuel and oxygen passageways 250, 260 of the downhole burner 60. The burner interface assembly 50 can comprise an outer housing 400 secured intermediate or at the downhole end of the main tubing string 40, an intermediate mandrel 410 at a downhole end of the intermediate tubing string 120, and an inner mandrel 420 at a downhole end of the inner tubing string 150.

The outer housing 400 has a bore which is adapted to releaseably connect with the intermediate mandrel 410. The intermediate mandrel 410 has an uphole portion 430 having a bore which is adapted to releaseably connect with the inner mandrel 420.

In greater detail, and with reference to FIG. 11, the outer housing 400 has a bore, an uphole end 440 and a downhole end 450. The uphole end 440 is adapted to fluidly connect to the main tubing string (not shown) and the downhole end 450 is adapted to fluidly connect to a pup joint which supports the downhole burner (not shown).

With reference to FIGS. 10 and 11, the intermediate mandrel 410 is fit within the bore of the outer housing 400 forming the intermediate annulus 140 therebetween. The intermediate mandrel 410, releaseably connected to the outer housing 400 at an intermediate latch assembly 470, has an uphole portion 430 which is adapted to fluidly connect to the intermediate tubing string 120. The uphole portion 430 further has a bore for releaseably connecting to the inner mandrel 420. In one embodiment, the uphole portion 430 is an inner latch housing.

The bore of the outer housing 400 has an inner surface 480 for forming a first intermediate latch 470A. The first intermediate latch 470A is formed adjacent a downhole end of the outer housing 400.

Further, the intermediate mandrel 410 has a second intermediate latch 470B formed at its downhole end. The second intermediate latch 470B is adapted to releaseably connect to the complementary first intermediate latch 470A to form the intermediate latch assembly 470.

With reference to FIGS. 10 and 12, the inner mandrel 420 is fit within the bore of the inner latch housing 430 and releasably connects with the intermediate mandrel 410 at an inner latch assembly 490. Similar to the intermediate latch assembly 470, the inner latch assembly 490 comprises a first inner latch 490A and a complementary second inner latch 490B.

As shown, the intermediate mandrel 410 is fit within the bore of the outer housing 400 for latching at the intermediate latch assembly 470 and sealing at a first seal 500 therebetween. The inner mandrel 420 is fit within the bore of the inner latch housing 430 for latching at the inner latch assembly 490 and sealing at a second seal 510 therebetween.

The intermediate annulus **140** is contiguous with an annular space between the outer housing **400** and the intermediate mandrel **410** and is in fluid communication with the fuel passageway **250** of the downhole burner **60**. The inner bore **180** is contiguous with a bore of the inner mandrel **420** and is in fluid communication with the oxygen passageway **260** of the downhole burner **60**. In this embodiment, the inner annulus **170** happens to terminate sealably at the second seal **510** for isolating the intermediate annulus **140** from the inner bore **180**.

The sealed inner annulus **170** isolates the intermediate annulus **140** from the inner bore **180**. This separation of the two discrete passageways provides a safety measure, ensuring that the fuel and the oxygen are separated by a buffer. In one embodiment, the sealed inner annulus **170** is also a sensing annulus for detecting leakage in the transport of the fuel and the oxygen. The sealed inner annulus **170** can be maintained in a vacuum or other pressure and is monitored for determining change in pressure indicative of a leak in either the intermediate annulus **140** or the inner bore **180**.

The intermediate latch assembly **470** can be any suitable releasable latch used in the industry, but in a preferred embodiment, the intermediate latch assembly is a type of latch assembly disclosed and claimed in US Pat. Serial No. 6,978,830, issued on Dec. 27, 2005, to MSI Machineering Solutions, Inc., located in Providenciales, Turks and Caicos.

Similar to the intermediate latch assembly **470**, the inner latch assembly **490** can be any suitable latch assembly used in the industry, including that disclosed and claimed in the aforementioned U.S. Pat. No. 6,978,830.

As best shown in FIG. **12**, an uphole end of the inner latch housing **430** is fit with a third seal **520** for sealing and isolating the intermediate annulus **140** from the inner annulus **170**. The inner latch housing **430** further has a second seal **510** for sealing and isolating the inner annulus **170** from the inner bore **180**.

For redundancy purposes, and to ensure sealing and isolating of the three discrete passageways, the first, second, and third seals **500**, **510**, **520** can be a plurality of individual seals in a stacked arrangement.

For greater safety and control of the fuel and oxygen passageways, and in a particular embodiment, the intermediate mandrel **410** can further comprise a backpressure valve assembly **600** for controlling the flow of the fuel and oxygen. Fuel is forced from the intermediate annulus **140** through the backpressure valve assembly by the first seal **500**.

The backpressure valve assembly **600** comprises two fluid bypass passageways, each having a backpressure valve. The fluid bypass passageways bypass the first seal **500**. A first bypass passageway **610**, having a first backpressure valve **620**, is in fluid communication with the intermediate annulus **140** for transporting the fuel from the main tubing string **40** to the fuel passageway **250** of the downhole burner **60**. A second bypass passageway **630**, having a second backpressure valve **640**, is in fluid communication with the inner bore **180** for transporting the oxygen to the oxygen passageway **260** of the downhole burner **60**.

Each of the backpressure valves comprises a ball **620**A, **640**A and a spring **620**B, **640**B, biased to apply a constant closing force on the ball, ensuring that the ball is sealingly fit within a ball seat **650**A, **650**B. The constant closing force is greater than the force applied by the differential fluid pressure between the static fluid pressure above the backpressure valves **620**, **640** and a reservoir pressure below the backpressure valves **620**, **640**. For either the fuel and/or oxygen to flow pass the backpressure valves **620**, **640**, the injection pressure of the fuel or oxygen must exert enough force to overcome the combined forces of the spring **620**B, **640**B and the reservoir pressure.

In one embodiment, the closing force biasing the ball of the backpressure valves **620**, **640** is based upon a differential pressure of 200 psi. In this embodiment, the injection pressure of both the fuel and oxygen must be sufficient to exert sufficient pressure to overcome the combined forces of the closing force and the force exerted by the reservoir pressure.

The injection pressure of the fuel or oxygen does not exceed the fracturing pressure of the particular target zone.

In Operation

In a broad aspect, hot combustion gases can be introduced into a target zone of a hydrocarbon reservoir and allowed to permeate therethrough. In one embodiment, introduction of the hot combustion gases can be accomplished by arranging a burner assembly, such as a downhole burner, for access to a cavity in a target zone of the hydrocarbon reservoir. Hot combustion gases from the burner assembly are permitted to permeate from the cavity and through the target zone.

Subsequently, water is also injected into the target zone and is also allowed to permeate through the target zone for interacting with the heated target zone and hot combustion gases therein. The interaction of the water with the hot combustion gases creates steam within the target zone for creating a drive front in the hydrocarbon reservoir. While some steam is likely to form in the cavity, primarily steam forms in the reservoir, spaced from the cavity itself, at a hot gas / water interface.

Applicant notes that the cavity can be any pre-existing cavity, naturally occurring or otherwise artificially created using downhole tools. A cavity, whether pre-existing or created can be worked on by a variety or combination of techniques. Cavity size and shape can be manipulated to extend or otherwise accommodate a combustion zone of the particular burner assembly and to form a cavity-to-hydrocarbon reservoir interface. The cavity reservoir interface, at a cavity envelope, forms an interface surface area between the hot combustion gases from the burner assembly and the target zone, and the larger the interface area, the better the access of the hot gases to the reservoir, particularly when the reservoir is characterized by a low permeability.

Simply, one accesses the cavity with a wellbore, whether the wellbore is pre-existing yet lacking a cavity, or the cavity is pre-existing and initially lacking a wellbore. Where wellbore exists or is formed, one runs the burner assembly down the wellbore to access the target zone. If the cavity does not exit, one is created. If the cavity was formed by means other than running in and operating the burner assembly, the burner assembly run downhole and arranged to access the cavity.

As shown in FIG. **16**A a cavity **1610** can be artificially created by reaming or hydraulic washing operations. Reaming of formations accessed by a wellbore is a known technique and includes tools and methods of bi-directional underreaming and backreaming. Hydraulic washing tools, including jetting, are also known for casing and formations. One accesses the target zone with a wellbore and runs in a tool downhole of the wellbore. In the case of a reaming tool, actuating the reaming tool such as by expanding the tool and reaming the target zone to form the cavity. In the case of a hydraulic washing tool, one actuates the washing tool for hydraulic washing of the target zone to form the cavity. The burner **60** is run in to access the cavity **1610**.

Any radial limitations of reaming might be further supplemented with additional hydraulic washing operations using appropriate combination reaming and hydraulic tools or staged independent tools.

As shown in FIG. **16**B, a cavity **1620** can be created artificially by combustion. One accesses the target zone with the wellbore. The burner assembly **60** is run in to the target zone. The burner assembly **60** is operated at a first condition for directing combustion into wellbore to form the cavity **1620**. The first condition may be at higher overall heat output or at higher temperatures so as to melt or otherwise degrade the target zone about the discharge of the burner assembly. Thereafter, the burner assembly **60** is operated at a second condition for directing combustion into the created cavity to form the hot combustion gases.

FIG. **16**C illustrates a pre-existing or naturally occurring cavity **1630**, such as geological cavities and cavities formed as a result prior operations in the hydrocarbon reservoir. One example of a cavity created by prior operations includes a sand-depleted cavity in a Cold Heavy Oil Production with Sand (CHOPS) reservoir. Applicants understand that in some cases of CHOPS production from the wellbore, a cavity **1630** can be formed about the producing well. Thus, before the burner assembly **60** is run downhole, there is a pre-existing cavity in the target zone about the wellbore.

Water is injected into the target zone by injecting water from a wellbore annulus **80**. In one embodiment, injection of water W can be accomplished by injecting water W through an annulus **60** about the burner assembly **60** for entering into the target zone. In an embodiment illustrated previously in FIG. **4**, the burner assembly **60** can have an annular seal **70** for sealing the annulus **80** and permitting injection of the water W into the target zone uphole of the annular seal. Accordingly, one seals the wellbore annulus **80** with an annular seal **70** at about the burner assembly **60** and water is injected into the target zone uphole of the annular seal **70**.

With reference to FIG. **17**, in another embodiment, and as described in Applicant's U.S. 61/560,468 and incorporated fully herein by reference, a burner assembly **1710** can have a shroud **1715** disposed at a downhole end **1720** surrounding a combustion zone **1730** thereof. As shown, the shroud **1715** can comprise an outer shroud **1740** and an inner shroud **1750** surrounding the combustion zone **1730** of the burner assembly **1710**. Water W from an outer annulus **1780** is injected into the target zone from about the shroud **1715**.

As shown, the burner assembly **1710** is illustrated depending from fuel and oxygen lines **1760** running downhole in a cased wellbore **1770**. In the context shown, the burner assembly **1710** is positioned for discharge of hot flue gases uphole of a cavity (not shown) of a target zone within a hydrocarbon-bearing formation. The shroud **1715** is fit about the combustion zone **1730** of the burner assembly **1710**.

The outer shroud **1740** is exposed to the target zone. An outer annulus **1780** is formed between the target zone and the outer shroud **1740**. Water injected above the burner assembly **1710** or in the annulus **1780** between the oxy/fuel conduit **1760** can flow into the target zone, along the outer annulus **1780**, and to a base of the outer shroud **1740**.

Injection of water W through the annulus **1780** comprises injection of water E into the target zone from about the outer shroud **1740**.

In greater detail for one embodiment, a combustion chamber **30** is formed by melting a target zone at a temperature sufficient enough to melt the hydrocarbon reservoir **10** at the target zone. Thereafter, a steady state combustion is maintained for sustaining a sub-stoichiometric combustion of the fuel and oxygen for producing hot combustion gases (primarily CO, $CO_2$, and $H_2O$) which enter and permeate through the reservoir **10**. The hot combustion gases create a gaseous drive front and heat the reservoir **10** adjacent the combustion cavity **30** and the wellbore.



Addition of water to the reservoir **10** along the casing annulus **80** above the combustion chamber **30** injects water into an upper portion of the reservoir **10** adjacent the wellbore for lateral permeation through the reservoir **10**. The lateral movement of the injected water cools the wellbore from the heat of the hot combustion gases and minimizes heat loss to the formation adjacent the wellbore. The water further laterally permeates through the reservoir **10** and converts into steam. The steam and the hot combustion gases in the reservoir **10** form a steam and gaseous drive front.

In more detail and referring again to FIGS. **1**, and **13**-**15**B, an injection well is cased and perforated at a target zone of the reservoir **10**.

A packer is set and a suitable depth of thermal cement is placed below the target zone. The thermal cement protects the packer from the downhole burner **60**.

Referring to FIG. **13**, a first main tubing hanger **100** is affixed to a wellhead **110**. A burner bottom hole assembly (burner BHA) **700** comprising a torque anchor **210**, the outer housing **400** of the burner interface assembly **50**, a pup joint **710**, and the downhole burner **60** are fluidly connected to a downhole end of a main tubing string **40**. The burner BHA **700** is run downhole to a depth for positioning the downhole burner **60** within a target zone. In one embodiment, the downhole burner **60** is positioned at about the midpoint of the target zone. Once in position, the main tubing string **40** is rotated to set the torque anchor **210** and the main tubing string **40** is hung from the main tubing hanger **100**.

As shown in FIGS. **1** and **3**, the main tubing string **40** and the casing **90** of the wellbore form a casing annulus **80** therebetween. The casing seal **70** between the burner housing **190** and the casing **90** seals the casing annulus **80**.

Referring to FIG. **14**B, an intermediate tubing hanger **130** is supported on the main tubing hanger **100**. With reference to FIGS. **14**A and **14**B, the intermediate mandrel **410** is fluidly connected to a downhole end of the intermediate tubing string **120**, and the concentric tubing **240** defining the oxygen passageway **260** extends downhole from the intermediate mandrel **410**. As shown in FIG. **14**B, the intermediate tubing string **120** is run downhole within the bore of the main tubing string **40**. The intermediate mandrel **410** is run downhole until it is tagged with the outer housing **400** of the burner interface assembly **50**. Tagging the intermediate mandrel **410** to the outer housing **400** involves releaseably connecting the outer housing **400** to the intermediate mandrel **410** at the intermediate latch assembly **470**, forming the intermediate annulus **140** therebetween. The intermediate tubing string **120** is pulled uphole to stretch the intermediate tubing **120** and remove any slack. The intermediate tubing string **120** is hung by the intermediate tubing hanger **130** and then cut to an appropriate length.

With reference to FIG. **15**A, an inner tubing hanger **160** is supported on the intermediate tubing hanger **130**. The inner mandrel **420** of the burner interface assembly **50** is fluidly connected to a downhole end of the inner tubing string **150**, and run downhole within the intermediate bore of the intermediate tubing string **120**. The inner tubing string **150** is run downhole until the inner mandrel **420** tags the intermediate mandrel **410** forming the inner annulus **170**. Tagging the inner mandrel **420** to the intermediate mandrel **410** involves releaseably connecting the inner mandrel **420** to the intermediate mandrel **410** at the inner latch assembly **490**. The inner tubing **150** is pulled uphole to stretch the inner tubing **150**, hung by the inner tubing hanger **160** and then cut to an appropriate length. The bore of the inner tubing string **150** defines the inner bore **180**.

The intermediate annulus **140** can be fluidly connected to a source of fuel, and the inner bore **180** can be fluidly connected to a source of oxidant, such as oxygen. The inner annulus **170** is sealed and is monitored. Any changes with the pressure within the sealed inner annulus **170** are indicative of a leak in either the intermediate annulus **140** or the inner bore **180**.

A further utility of the backpressure valve assembly is to assure successful latching and continuity of the intermediate and inner tubing string at the burner interface assembly, an inability of the either passageway to retain pressure up to the opening pressure of the valves being indicative of a problem in the connections of one form or another.

The fuel can be delivered down the intermediate annulus **140** passing through the first bypass passageway **610** and first backpressure valve **620** and to the fuel passageway **250**. Similarly, oxygen can be injected down the inner bore **180**, through the second bypass passageway **630** and the second backpressure valve **640** to the oxygen passageway **260**. Both the fuel and oxygen enter the nozzle **200** for combustion. The first and second backpressure valves **620**, **640** creates a back-pressure greater than that static head to surface pressure, ensuring that the flow of the fuel and oxygen can be controlled from the surface by controlling the flow rate of the fuel and oxygen. If the flow rate of the fuel or oxygen does not create enough pressure to overcome the pressure exerted by the closing force of the backpressure valve spring **620**B, **640**B and the reservoir pressure, fuel and oxygen cannot pass the first and second backpressure valves **620**, **640**.

After the burner assembly **20** is positioned within the target zone, the reservoir **10** can be initially flooded with water. Water is injected down the casing annulus **80** to enter the reservoir **10** through the perforations for increasing the reservoir pressure adjacent the wellbore. The fuel is then injected downhole. After a sufficient amount of time to ensure that the fuel has entered the target zone downhole, the fuel is doped with an accelerant, a pyrophoric compound such as triethylborane or silane, sufficient for igniting the fuel. Oxygen is injected to light off the downhole burner **60**. The accelerant is discontinued to create a stable flame for combustion. A stable flame can be maintained by controlling the rate of the fuel and oxygen. The fuel and oxygen are controlled to combust at a temperature to create a combustion cavity **30** sufficient to melt or otherwise form a cavity **30**.

In one embodiment, the downhole burner **60** can be lit off and operated at a first condition to form a minimum stable flame temperature of about 2800° C. At such a temperature, it is believed that the casing **90** and the surrounding reservoir **10** downhole of the burner **60** would melt, forming the combustion cavity **30**. The burner **60** is then located or arranged generally uphole of the cavity. As the combustion cavity **30** expands, molten material will flow and pool at a bottom of the combustion cavity **30** above the thermal cement for forming an impermeable glassy bottom. Further, the heat from the flame continues to be transferred to the lateral walls by a combination of radiant heat transfer and hot combustion gases permeating into the reservoir **10**. Melting and enlargement of the combustion cavity **30** ceases when the combustion cavity **30** is sufficiently large enough that the heat transfer from the combustion is below the melting point of the reservoir **10**. The lateral walls of the combustion cavity **30** remain porous and permeable, perhaps in a sintered state.

Once the combustion cavity **30** has been formed, the fuel and oxygen are controlled to continue steady state combustion for creating and sustaining hot combustion gases for flowing and permeating into the target zone.

Further, the steady state combustion of the fuel and oxygen is also under sub-stoichiometric conditions, limiting the amount of oxygen available for combusting with the fuel. The limited amount of available oxygen ensures that there is no excess oxygen available for flowing into the reservoir **10**. Excess oxygen flowing into the reservoir **10** may result in additional combustion within the reservoir **10** and result in some coking therein.

Water is delivered down the casing annulus **80**. The casing seal **70** directs the water out the perforations and into the target zone concurrently as hot combustion gases are created and sustained at steady state. The injected water and hot combustion gases in the target zone interact to form a drive front comprising steam and hot combustion gases.

The present process further protects the reservoir **10** from permeability degradation due to chloride scaling by keeping the chlorides in solution. Most chloride scaling is caused by introducing water with a dissimilar ion charge during water flooding. Increasing temperature and/or pressure typically improves solubility of chlorides. The risks of chlorides deposition are reduced as both temperature and pressure increase with the introduction of heat and $CO_2$ (from the hot combustion gases). Higher $CO_2$ concentrations in formed emulsion increases carbonate solubility. The process can be operated to continually produce incremental $CO_2$, gradually increasing concentrations as the flood progresses.

Risk of chloride scaling is further mitigated by maintaining an 80% steam quality downhole which keeps chlorides in solution. Untreated produced water typically contains upwards of 50,000 ppm of total dissolved solids, which is typically treated prior to being passed through boilers for conventional stem flood processes. Control of the mass and heat balance of the combustion process permits management of the steam generation in the target zone to be at about 80% steam quality. The lower steam quality ensures that there is a sufficient water phase to keep all dissolved solids in solution and treatment of the produced water is not required.

In an alternate embodiment, fuel can be injected downhole through the inner bore **180**, while the oxygen can be injected down through the intermediate annulus **140**.

Further, in an alternate embodiment, where regulation may prohibit injection of fluid down the casing annulus **80**, water can be injected down one o the other passageways. For example, water could be injected down the intermediate annulus **140** for injection at the burner assembly for communication with the hydrocarbon reservoir. In such an embodiment, the inner annulus **170** can be used to inject fuel or oxygen, instead of being used as a sensing annulus for detecting leaks, oxygen or fuel could continue to be injected down in the inner bore **180**. Further, as those skilled in the art would understand, the intermediate annulus **140** would have a water injection port in the burner assembly and placed in fluid communication with the reservoir to allow the injected water to flow into and permeate through the reservoir and a flow through packer can be used to isolate the burner assembly **20**. One approach is to locate a flow-through packer at about the burner assembly for sealing the casing annulus above the water injection port. Water injected from the intermediate annulus would exit from the water injection port and into an injection annulus formed in the casing annulus between the packer and the casing seal.

Further still, yet, in a further alternate embodiment, the inner tubing string **150** can be eliminated such as to reduce costs. In such an embodiment, the main tubing string **40** can be disposed within the casing **90** forming the casing annulus **80**, and the intermediate tubing string **120** can be disposed in the main tubing string **40** forming the intermediate annulus **140**. The intermediate tubing string **120** would have a bore forming the inner bore **180**. This embodiment would not have the inner annulus **170** to serve as a sensing annulus for detecting leaks in the intermediate annulus **140** and/or the inner bore **180**.

The embodiments of the invention for which an exclusive property or privilege is claimed are defined as follows:

**1**. A process for creating a drive front in a hydrocarbon reservoir for enhanced oil recovery comprising:

accessing a cavity within the hydrocarbon reservoir with a wellbore;

arranging a burner assembly in the wellbore uphole of the cavity;

creating hot combustion gases with the burner assembly, directing the hot combustion gases from the burner assembly into the cavity and sustaining hot combustion gases therein;

injecting water into the hydrocarbon reservoir uphole of the cavity, the water entering into and permeating into the hydrocarbon reservoir and interacting with the hot combustion gases therein for creating steam in the hydrocarbon reservoir; and

forming a steam drive front in the hydrocarbon reservoir.

**2**. The process of claim **1** further comprising artificially creating the cavity in the hydrocarbon reservoir.

**3**. The process of claim **2** wherein creating the artificially-created cavity comprises extending a combustion zone of the burner assembly into the cavity.

**4**. The process of claim **2** wherein creating the artificially-created cavity comprises forming an interface area between the hot combustion gases from the burner assembly and the hydrocarbon reservoir.

**5**. The process of claim **2** wherein creating the artificially-created cavity comprises mechanically-forming the cavity.

**6**. The process of claim **5** wherein creating the mechanically-created cavity comprises reaming the target zone.

**7**. The process of claim **5** wherein creating the mechanically-created cavity comprises

accessing the target zone with a wellbore;

running a reaming tool downhole of the wellbore; and

actuating the reaming tool and reaming the target zone to form the cavity.

**8**. The process of claim **2** wherein creating the artificially-created cavity comprises hydraulic washing of the target zone.

**9**. The process of claim **2** wherein creating the artificially-created cavity comprises

accessing the target zone with a wellbore;

running a washing tool downhole of the wellbore; and

actuating the washing tool for hydraulic washing the target zone to form the cavity.

**10**. The process of claim **2** wherein creating the artificially-created cavity comprises

reaming the hydrocarbon reservoir downhole of the wellbore; and

actuating a washing tool for hydraulic washing the reamed hydrocarbon reservoir to form the cavity.

**11**. The process of claim **2** wherein creating the artificially-created cavity comprises:

operating the burner assembly at a first condition for directing combustion into wellbore to form the cavity.

**12**. The process of claim **11** further comprising:

operating the burner assembly at a second condition for directing combustion into the created cavity to form the hot combustion gases.

**13**. The process of claim **1** wherein the cavity is a pre-existing cavity comprising:

accessing the pre-existing cavity with a wellbore; and

running the burner assembly down the wellbore to access the cavity.

**14**. The process of claim **13** wherein the pre-existing cavity is a naturally-forming cavity.

**15**. The process of claim **13** wherein the hydrocarbon reservoir is a Cold Heavy Oil Production with Sand (CHOPS) reservoir and prior to arranging the burner assembly comprising

producing from the wellbore and forming the pre-existing cavity in the hydrocarbon reservoir thereabout.

**16**. The process of claim **1** wherein injecting water into the hydrocarbon reservoir further comprises injecting water from a wellbore annulus between the burner assembly and the wellbore.

**17**. The process of claim **16** further comprising:

sealing the wellbore annulus with an annular seal at about the burner assembly; and wherein the injecting water from the annulus further comprises

injecting water into the target zone uphole of an annular seal.

**18**. The process of claim **1** wherein the burner assembly further comprises a shroud disposed at a downhole end of the burner assembly and surrounding a combustion zone thereof, and wherein the injecting water from the wellbore annulus further comprises injecting water into the hydrocarbon reservoir from about the shroud.

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